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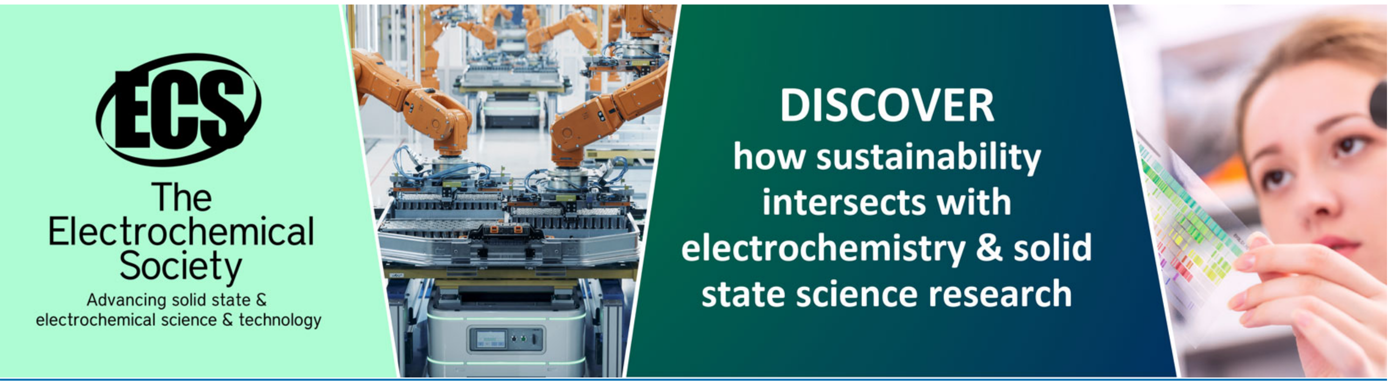

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Review of Liquid-Argon Detectors Development at the CERN Neutrino Platform

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Abstract. The European Strategy for Particle Physics of 2013 classified the short and long baseline neutrino program as one of the four highest-priority scientific objectives with required international infrastructure. In this framework, CERN has created a "Neutrino Platform” for detector R&D and support to future international neutrino experiments, as well as to provide a basis for European neutrino communities towards contributing to the US and Japanese projects. In particular, significant R&D effort is made on the Liquid Argon Time Projection Chamber technologies. As a part of the Neutrino Platform facilities, CERN is constructing a large test area (EHN1 extension of the SPS North Area) with charged beams capabilities devoted to neutrino detectors. An overview will be given of the main Liquid Argon neutrino detector projects presently under development in the framework of the CERN Neutrino platform.

1. The future neutrino landscape

The understanding of the neutrino sector is a worldwide priority, promising physics beyond the Standard Model of particle physics in a unified theoretical framework that goes from the electroweak scale to the highest energy scales. The rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino program exploring CP violation and the mass hierarchy in the neutrino sector.

The European Strategy for Particle Physics (ESPP) of 2013 classified the long-baseline neutrino program as one of the four highest-priority scientific objectives with required international infrastructure. The currently planned new large neutrino oscillation physics facilities will focus on probing CP-violation in the neutrino sector, determining the neutrino mass hierarchy, looking for sterile neutrinos (i.e. testing the three neutrino flavor paradigm), proton decay (through kaon channels), and with an ability to observe supernova neutrinos. In Japan an extensive upgrade of Super-Kamiokande through international cooperation (Hyper-Kamiokande [1]) is considered a priority project. In the US a large international collaboration is being formed (DUNE collaboration [2]) to perform, in the next decades, long (1300km) baseline experiment using precise near detectors and multi-kton liquid Argon far detectors exposed to a dedicated intense neutrino beam. On a shorter time scale, a complementary short base line neutrino program (SBN collaboration [3]) is in preparation at FNAL, aiming at the search of additional sterile neutrino flavors to clarify the long lasting LSND and MiniBooNE anomalies, using multiple liquid Argon detectors exposed at the Booster neutrino beam.

2. The CERN neutrino platform

CERN has a long tradition in neutrino physics, starting from the Gargamelle detector at CERN in 1973 that provided the first evidence for the weak neutral current, and in the late 1970s, with BEBC, CDHS and CHARM exposed to the SPS neutrino beam to further unveil the neutrino's identity. A milestone came in 1989, when precise measurements at LEP showed that there are three, and only three, light neutrino species that couple to the Z boson. This was followed by searches for neutrino oscillations by the NOMAD and CHORUS experiments during the 1990s. More recently, from 2006 to 2012, CERN sent the CNGS muon-neutrino beam to the ICARUS and OPERA detectors at the Gran Sasso National Laboratory (LNGS), 732 km away in Italy, leading to the observation of the ν_μ to ν_τ transition.

In the framework of the ESPP program, CERN has now opened a platform for neutrino detector development, integrated into the present CERN Medium Term Plan, to promote R&D and offer support to international collaborations in the field of cryogenics, magnet technology, integration and assembly techniques, as well as to provide a basis to unify the European neutrino communities towards contributing to the US and Japanese projects. In particular, significant R&D effort is devoted to the liquid Argon Time Projection Chamber (LAr-TPC) technologies.

CERN is currently building a large neutrino test area (EHN1 extension) with charged beam capabilities that will be available in 2017. Moreover, CERN is collaborating with FNAL on the infrastructures of the Long-Baseline Neutrino Facility (LBNF) and of the SBN facility and is actively participating to the short and long baseline neutrino program. A neutrino-theory group is also planned within the Neutrino Platform to help promoting research in theoretical neutrino physics at CERN.

So far, around 50 European institutes have signed up as members of the Neutrino Platform. The Neutrino Platform projects, submitted to the CERN-SPSC and approved as experiments, are:

- NP01: WA104, overhauling of the ICARUS T600 LAr-TPC in view of its use as far detector for FNAL short baseline program;
- NP02: WA105, double phase LAr-TPC demonstrator and ProtoDUNE-DP engineering prototype for a double phase LAr-TPC for DUNE;
- NP03: PLAFOND, general R&D framework;
- NP04: ProtoDUNE-SP, engineering prototype for a single phase LAr-TPC for DUNE;
- NP05: Baby Mind, a muon spectrometer for the WAGASCI experiment at T2K;
- LoI-243: ArgonCube: R&D for a highly modular LAr-TPC concept.

2.1. The LAr-TPC technology

The innovative LAr-TPC detection technique is characterized by the precise imaging and calorimetric reconstruction capabilities of any ionizing track in neutrino processes or other rare events with a performance comparable to that of a traditional bubble chamber. In addition the LAr-TPC is a fully electronic, continuously sensitive, self-triggering detector and potentially scalable to very large masses (several kt). The operating principle is based on the fact that in highly purified liquid Argon free electrons from ionizing particles can be easily transported over macroscopic distances (meters) with the help of a uniform electric field to a multi-wire anodic structure placed at the end of the drift path. The recording of arrival time and position on the anode wire planes allows full 3D event reconstruction. The prompt scintillation light provides the t_0 of the interaction and the absolute position of the event along the drift coordinate.

In the following sections, a focus will be given on the projects based on the LAr-TPC technologies, chosen for the next generation multi-kton detectors for neutrino physics in US, after the successful pioneering work of ICARUS in Europe followed by ArgoNeut/LarIAT/MicroBooNE in US.

3. The ICARUS T600 overhauling program

The ICARUS T600 LAr-TPC [4], built in the year 2000 as a technology demonstrator, has been successfully operated (2009-2013) at LNGS, completing a three-year physics run at the CNGS

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neutrino beam and collecting atmospheric neutrino events. It is so far the largest LAr-TPC ever operated and is composed by:

- 2 independent identical T300 modules, 3.6x3.9x19.6 = 275 m^3 each: 476 t LAr active mass;
- 4 TPC chambers, 2 in each T300, 3 wire planes 3 mm apart, 52000 wires with 3 mm pitch, directions at 0°, ±60°;
- 74 photomultiplier tubes (PMTs), VUV sensitive with TPB wavelength shifter;
- evacuable aluminium cryogenic vessel;
- continuous recirculation and filtering (Oxysorb/Hydrosorb) in liquid and gas phases allowing to reach free electron lifetime exceeding tens of milliseconds;
- low noise "warm" front-end electronics and VME-based digitization/DAQ system.

At the end of 2014, the T600 detector was transferred to CERN and is currently being refurbished by the Neutrino Platform's WA104 team, as a joint INFN-CERN program, before being shipped to FNAL for the SBN program [3]. This program has been approved to address the yet unexplained results from the LSND experiment at Los Alamos National Laboratory in the 1990s, which hinted at the existence of a fourth, possibly "sterile", neutrino. The result was followed up by the MiniBooNE experiment at FNAL, which also saw deviations, albeit different again, from the expected signal.

ICARUS will be installed at 600 m downstream from the source of the ~ 1 GeV neutrino beam at FNAL's booster ring. It will be the farthest of three detectors in the line of the beam after the Short Baseline Neutrino Detector (SBND, currently under design) and MicroBooNE (already operational). The three detectors employ similar LAr-TPC's allowing the study neutrino oscillations with high details and minimized systematic errors.

The T600 overhauling campaign at CERN aims at improving the performances of the detector with the introduction of technological developments to match the additional requirement of operating on surface with high interaction rates and cosmic ray background. It concerns many parts of the T600 LAr-TPC (figure 1):

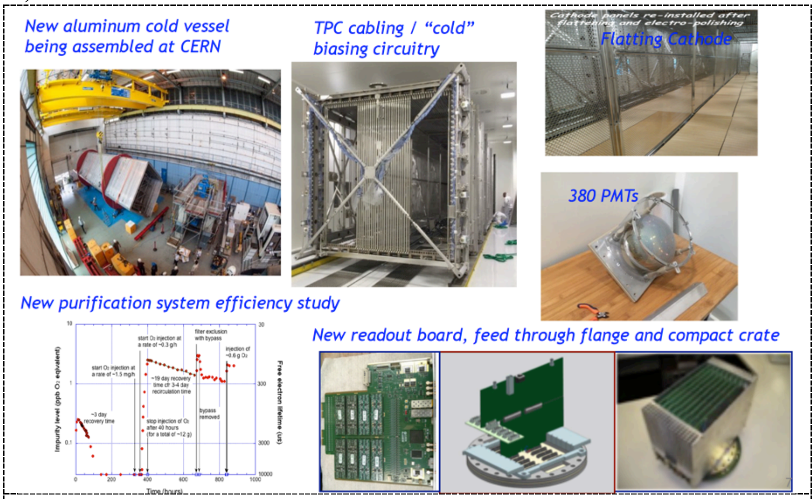

Figure 1. Overhauling of the ICARUS T600 detector at CERN in view of its use as far detector on the SBN experiment at FNAL.

- Upgrade of the light collection system: 360 8''PMTs behind wire planes (~5% photo-cathode coverage) to precisely localize events in drift window; fast response, ~ns resolution, to exploit the 2ns/19ns bunched beam structure for cosmic rays rejection;
- New j-fet based low noise (<10^3 el.) "warm" electronics, 2.5 MHz AD converters and programmable FPGAs (for triggering, ROI identification, online data compression), with "compact" serial bus architecture and optical links for faster transmission rate (Gbit/s);
- Flattening of existing cathode panels, to get a better electric field uniformity for a more accurate muon momentum measurement by multiple coulomb scattering;

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- New LAr containers (cold vessels) made by extruded aluminium profiles welded together, to form a ultra-clean and ultra-high-vacuum-tight container compliant with EU & US rules; purely passive insulation bed (≈ 6.6 kW, 10 - 15 W/m^2);
- New cryogenics system and (Cu based) purification equipment matching FNAL requirements.

Moreover, the Cosmic Ray Tagger and data filtering/selection tools are items common to the whole SBN program and they are being jointly developed for the 3 SBN detectors. The experiment will benefit from European and US expertise in automatic event reconstruction and large data handling.

4. The DUNE Long base line neutrino oscillation program

The DUNE long-baseline experiment [2] will include a far detector consisting of four 10-kt active LArTPC modules located in the Sanford Underground Research Facility, 1300 km away from FNAL where a dedicated neutrino beam will be constructed. The modules are planned to be of two different designs, single-phase (which uses a technology very similar to that in ICARUS) and dual-phase, in which ionization electrons are pulled into a gaseous Ar region above the liquid where they are first amplified and then read-out in ThickGEM-based anodic planes.

4.1. The ProtoDUNE program at CERN

To enable both types of LAr-TPC detectors to be scaled up to the multi-kiloton level required by DUNE, two kt-scale prototypes (ProtoDUNE-SP for Single Phase [5] and ProtoDUNE-DP [6] for Dual Phase) are being built in the framework of the CERN Neutrino Platform.

Both ProtoDUNE-SP and -DP will be exposed to test beam in 2018 in a new test facility of (~53'000 m^3) currently under construction as an extension of the EHN1 experimental area at CERN's Prévessin site (figure 2). The civil-engineering works of the EHN1 extension have been completed with beneficial occupancy from September 2016. The test facility will comprise two dedicated beam lines (H2 for ProtoDUNE-DP, H4 for ProtoDUNE-SP) providing tertiary beams of: (±) π, K, p + e contamination at low energies, pure electron beams, parasitic μ halo, with an energy range of 0.2-12 GeV/c, similar to that of particles induced by neutrino interactions in DUNE, and momentum bite of 5% (that can be reduced to 1% with integrated spectrometer measurements).

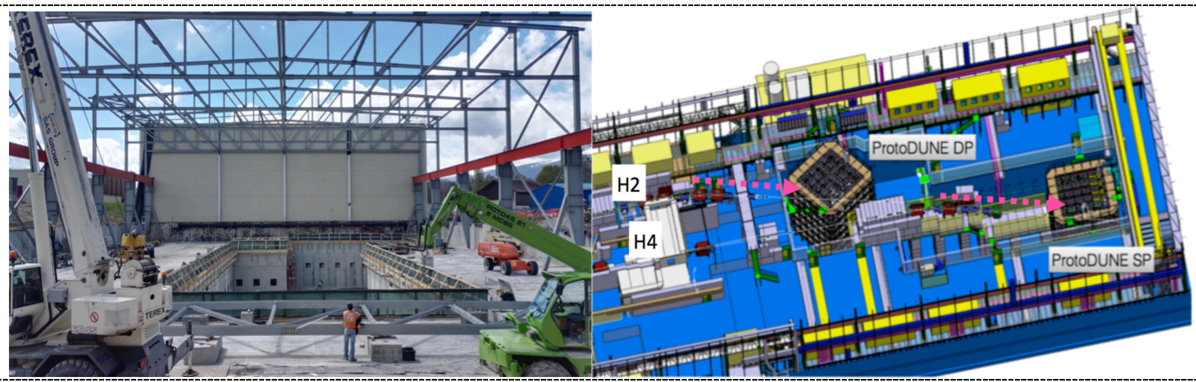

Figure 2. The new neutrino experimental area in the EHN1 extension. Locations of ProtoDUNE-SP and -DP are indicated as well as the respective beam lines H4 and H2.

The construction and operation of ProtoDUNE-SP and -DP will serve to validate the cryostat technology and associated cryogenics, the networking and computing infrastructure that will handle the data and simulated data sets. It will also benchmark the principal technical solutions for the DUNE far detector components and, if they are found to be fully adequate, to endorse them. Operating the detectors in real experimental conditions and for an extended period will allow for a full characterization of TPC anodic planes read-out schemes, the layout of the read-out electronics, the TPC field cage and HV system, the light detection and the trigger systems.

Test runs with the charged-particle beam at EHN1 extension at the end of 2018, will provide critical calibration measurements necessary for precise calorimetry. They will also enable the collection of valuable data sets for optimizing the event reconstruction algorithms – i.e., for finding interaction vertices and particle identification – and ultimately for quantifying and reducing systematic uncertainties for the DUNE far detector, thus significantly improving its physics reach.

Anticipated measurements in 2018 with pions and protons:

- Measure calibration constants (energy) and validate reconstruction tools and simulations;
- Measure π^+/π^- differences and topological shower differences (< 1 GeV);
- Measure pion interaction cross sections;
- Develop PID for stopping pions and protons; μ/π discrimination (≤ 1 GeV);
- Measure π^0 for NC backgrounds and calibration;
- Study e-γ separation (~ 1-2 GeV).

Similarly with electrons:

- Study e-γ separation (< 2 GeV); need good angular spread;
- Calibrate e.m. showers (sub GeV - multi-GeV).

And with muons:

- Study Michel electrons, calibrate Bethe-Bloch, study μ-capture on Ar (≤ 1 GeV).

4.2. The membrane cryostats

The construction of very large size (10-100 kton) cryostats is out of reach with traditional vacuum insulated methods. A new technology is being developed based on LNG industrial solutions. The structural support is realized by an outer steel structure containing specially designed insulating panels insulation, while the liquid containment is performed by a corrugate membrane made of thin steel panels welded together (licensed by GTT, France) is an attractive solution for the latter component. The thermal insulation is passive, based on glass reinforced polyurethane foam (GRPF) layers, interspersed with pressure distributing layers of plywood.

The first large-scale cryostat tank constructed on this technique is that of the WA105 3×1×1 m^3 pilot detector at CERN. Its operation will allow validation for ultra-high purity environment with the development of dedicated leak detection methods of the membrane welding and the piston purge technique to evacuate air with Argon gas before filling with LAr.

The ProtoDUNE vessels are being constructed at the EHN1 neutrino building. The nearly identical membrane cryostats for single and double phase ProtoDUNE will have internal size of 7.9 x 8.5 x 8.1 m^3 (770 t total LAr mass) and an active volume of 6 x 6 x 7 m^3 (-SP) and 6 x 6 x 6 m^3 (-DP) as determined by physics measurement (energy bias studies require full longitudinal and lateral containment of hadronic showers) and engineering (to test full scale-components assembled into functional sub-unit).

The cryostats are engineered and constructed by CERN with a design scalable to the DUNE Far Detector dimensions. The outer steel structure is under installation, the insulation is being delivered and the membrane engineering as well as the detector penetrations have been finalized. The cryostats will be ready by middle 2017. They will be equipped with similar cryogenic systems and will adopt similar operation procedures: air evacuation through piston purge with GAr, LAr/GAr cool down, LAr filling, continuous LAr circulation/purification with cryogenic LAr pumps.

4.3. The ProtoDUNE SP detector

The ProtoDUNE-SP TPC (figure 2) [5] comprises two drift volumes, defined by a central cathode plane that is flanked by two anode planes, both at a distance of 3.6 m, and a field cage (FC) that surrounds the entire active volume, which is of 6 m high, 7.2 m deep and 7.2 m wide drift direction).

Each anode plane is constructed of three Anode Plane Assemblies (APAs), 6 m high by 2.3 m wide. Each APA consists of a frame holding three parallel planes of wrapped wires; the wires of each plane are oriented at different angles with respect to those on the other planes to enable 3D reconstruction. The wire pitch is 4.5 mm, and each APA holds a total of 2,560 wires.

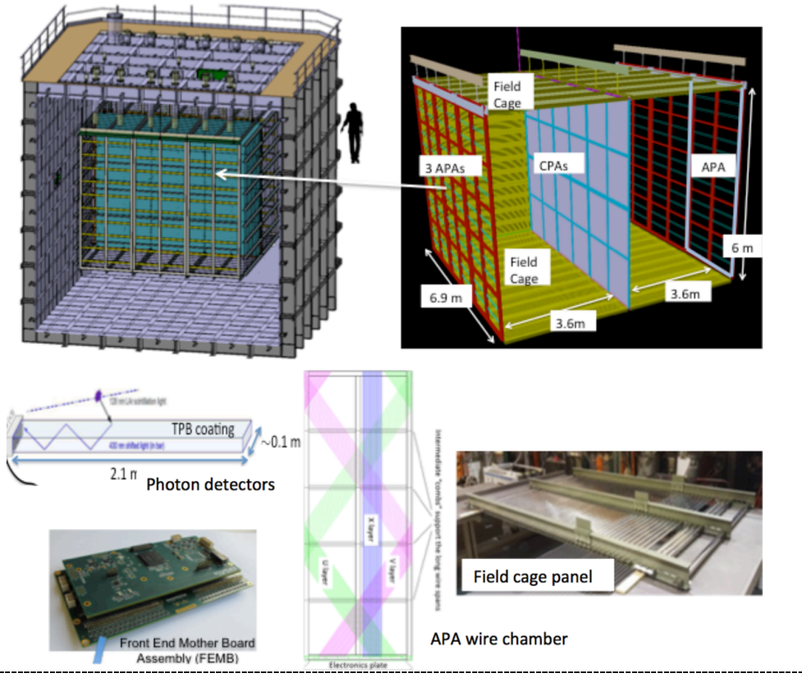

Figure 3. Schematics of the ProtoDUNE-SP detector in its membrane cryostats. The main detector components are also shown.

The cathode plane, also called the Cathode Plane Assembly (CPA) is an array of 18 (six wide by three high) CPA modules, which consist of G10 frames, each 1.18 m wide and 2 m high, that hold thin sheets with a resistive coating on both sides. The CPA is held at −180kV providing the 500 V/cm drift field in the 3.6-m-deep drift regions. Uniformity of the electric field is guaranteed by a modular field cage (FC) made of open metallic profiles surrounding the drift volume and electrically connected to each other through a resistor divider that degrades uniformly the voltage from the CPA to the APA.

The cold electronics (CE), mounted onto the APA frame, thus immersed in LAr, amplifies and continuously digitizes the induced signal waveforms on the sense wires at 2 MHz, and transmits these data to the Data Acquisition system (DAQ). Data are transmitted through the buffer to disk, then to the central CERN Tier-0 Computing Center, and finally to other partner sites for processing.

The modular photo-detection system (PDS) is integrated into the APA frames. Each PDS module in the system consists of a thin, wavelength-shifting radiator plate mounted on a wavelength-shifting, bar-shaped light guide. The plates are coated with a layer of tetraphenyl-butadiene (TPB) that converts incoming VUV (128 nm) scintillation photons to longer-wavelength photons, in the visible blue range. Half of the converted photons are emitted into the bar, a fraction of which are then internally reflected to the bar's end where they are detected by silicon photomultipliers (SiPMs). Each APA frame is designed with ten bays into which PDs are inserted after the TPC wires have been strung.

Given the innovative LAr-TCP design concepts, an intense R&D phase was successfully conducted at CERN on the CPA and FC to optimize the design in terms of HV reliability and active volume maximization, to select materials for cryogenic use and for LAr purity compatibility.

4.4. The ProtoDUNE DP detector

The goal of ProtoDUNE-DP [6] is the construction of a large-scale demonstrator of the dual-phase liquid Argon TPC, with a fiducial volume of 6×6×6 m^3 (figure 4), as required for the development and proof-check of industrial solutions, and to validate technologies on a large scale, such as:

- construction and operation of a large field cage;

- very high voltage (up to 600 kV) generator and related cryogenic feed-through;
- large area micro-pattern charge readout;
- cold front-end charge readout electronics;
- long-term wavelength shifter coating of photomultipliers;
- integrated light readout electronics.

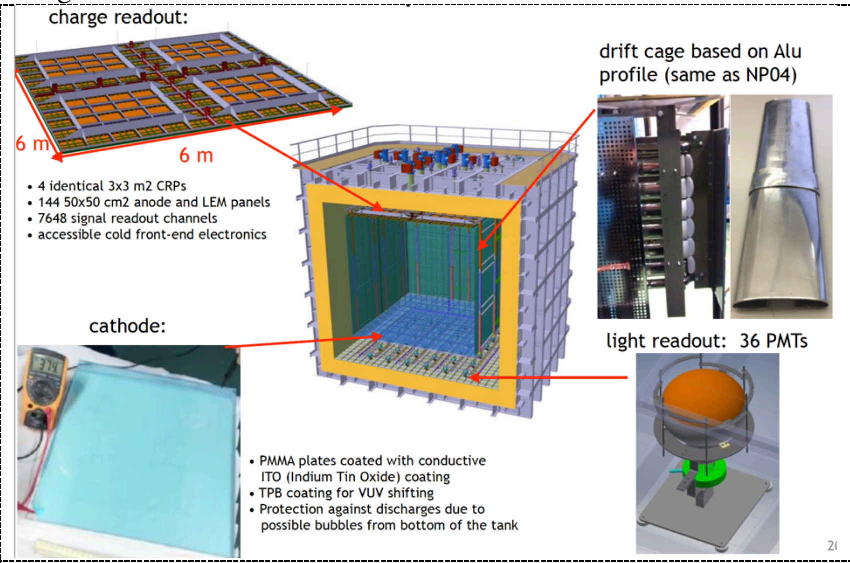

Figure 4. Schematics of the ProtoDUNE-DP detector in ITS membrane cryostats. The main detector components are also shown.

Charge multiplication in the gaseous phase is achieved with the use of the Large Electron Multiplier (LEM or Thick-GEM), where a very intense electric field is produced inside small holes (typically with 50 μm diameter and 80 μm pitch). The charge is then collected on anodes manufactured from a single multi-layer printed circuit board, providing symmetric charge sharing between the two orthogonal views and a space resolution of 3 mm on each view. On small-scale prototypes, charge resolutions close to 8% have been obtained on both views, with an effective LEM gain close to 30. For ProtoDUNE-DP the anodic structure is built out of four the $3x3m^2$ Charge Readout Plane units (CRP) as foreseen for the 10 kton Dual-Phase DUNE Far Detector.

The drift will be 6 m long (HV= -300 kV for E_{drift} = 500 V/cm) defined by a cathode at the bottom of the cryostat, made of PMMA plates coated with conductive ITO (Indium Tin Oxide) and deposited with TPB for VUV shifting, and a field cage built with a modular concept as that of ProtoDUNE-SP.

A cost-effective solution for front-end electronics and data acquisition consists of analog preamplifiers implemented in CMOS ASIC circuits for high integration and large scale affordable production, connected to micro-TCA crates. The ASIC analog amplifiers are integrated on a feed-through flange terminating the chimneys on the roof of the tank, under the insulation layer, in order to be cooled to a temperature near that of liquid argon and thus exploit the reduction of electronics noise with temperature and with the reduced capacitance of cables for the analog signal, which are shorter than in the case of ASICs placed outside the cryostat. The micro-TCA crates for charge digitisation will be placed in the warm zone on top of the cryostat. The front-end electronics thus remains accessible during the whole duration of the experiment.

Scintillation light provides the t_0 for interactions and, in principle, complementary information for energy reconstruction and particle identification. The light readout system will consist of 36 photomultipliers (8" Hamamatsu R519mod2), placed in LAr below the cathode plane and protected from the HV by a grounded grid.

ProtoDUNE-DP is preceded by a pilot detector [7] with a fiducial volume of $3x1x1\ m^3$ (4t) which has been engineered and assembled at CERN and will operate with cosmic muons starting from the end of 2016. It includes a Charge Readout area of 3x1 m^2 with adjustable gain of 10-20, cold (accessible) F/E electronics in chimneys and max drift length of 1 m. It will demonstrate detector feasibility and principles, components engineering, cryostat and cryogenics design and construction.

4.5. Additional activities at the Neutrino Platform

Complementing the detector hardware developments is work on reconstruction of LAr-TPC data, an area that still proves challenging. CERN is at the frontier, searching out the most advanced methods of computer visualizations and machine learning to extract physics information from the data.

CERN is also contributing in the developments ArgonCube [7]: a modular LAr-TPC proposed (Bern Univ.) as alternative design for (Magnetized) DUNE Near Detector. Advantages are: shorter drift-times, less stringent liquid Argon purity requirements, less pileup & lower voltage, scintillation light contained with less optical pileup, accurate trigger & veto. Pixel readout with live 3D reconstruction with reduced ambiguities is also proposed. Several modules could share the same LAr bath. A prototype, engineered by Bern and CERN, is under construction containing 4 modules, 1 with reference wire readout (Sheffield), and 3 with Pixel readout (Bern, CERN). First TPC tests are expected by end 2016 using pixel demonstrator (successfully operated on smaller prototypes in Bern).

Finally the CERN Neutrino Platform is also working on components for Japan's neutrino program and plans to involve a neutrino-theory working group to strengthen the connections between CERN and the worldwide community and help to promote research in theoretical neutrino physics at CERN.

5. Summary

The CERN Neutrino Platform is a unique R&D framework for the International Neutrino community. It will provide immediate physics potential with the exploitation of the short baseline at FNAL (and the new T2K near detector). Major contribution will be given to the infrastructure of LBNF and to the design and construction of new large detector prototypes. Generic R&D on new detectors and data handling will also be possible. The participation in the construction, commissioning and physics exploitation of the new neutrino facilities is also on going.

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