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# GLACIER for LBNO: physics motivation and R&D results

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**Abstract**

The double phase liquid argon time projection chamber is an exciting new technology for neutrino detectors. This technology is known to provide excellent tracking and calorimetry performance that can outperform other techniques. In this context GLACIER is a proposed giant double phase liquid argon underground neutrino observatory scalable to masses of 100 kton. As proposed by the future European Long Baseline Neutrino Oscillation program (LBNO), a neutrino beam from CERN with GLACIER as far detector would allow to precisely measure the neutrino mixing parameters, determine the neutrino mass hierarchy and test the existence of the CP-violating phase. At the same time, the detector could conduct astroparticle experiments of unprecedented sensitivity. GLACIER relies on novel technologies which are currently being tested on small scale prototypes. In the near future, we also plan to construct and operate larger devices.


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## 1. Introduction

The next milestones for future neutrino oscillation experiments are now well defined: the determination of the mass hierarchy and the measurement of the CP-phase of the PMNS matrix ($\delta_{CP}$) to establish if there is or not CP-violation in the lepton sector. In this context LBNO [1] aims in it's first 5 years of running to unambiguously determine the mass hierarchy to a better than $5\sigma$ C.L. over the whole $\delta_{CP}$ phase space and give evidence for CP-violation at the $3\sigma$ C.L [2]. LBNO will achieve those goals by exploiting the $L/E$ dependence of the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance probabilities with a wide-band beam at a baseline of 2300 km. In order to precisely measure the oscillation pattern as a function of the neutrino energy the far detector will consist of a 20 kton double phase Liquid Argon Time Projection Chamber (LAr-TPC). In a second phase of the experiment, the design is contemplated to be scaled to 50 kton to achieve a full $\delta_{CP}$ discovery.

The double phase LAr-TPC is a high-resolution tracking and calorimetric device which offers many advantages. In addition to its large mass and good energy resolution, it is known to provide high efficiency for $\nu_e$ charged current interactions with high rejection power against $\nu_\mu$ neutral and charged currents backgrounds in the GeV and multi-GeV region. Moreover the good granularity allows for particle identification through the measurement of $dE/dx$ versus range. Unlike in the case of a single phase LAr TPC, where

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the charge image is readout with wire planes in the liquid, the double phase readout takes advantage of the charge multiplication in gas argon yielding a larger signal to noise ratio and overall better image quality. The amplification of the drifting charges in gas allows to build LAr TPCs to the scales required by the LBNO far detector. The far site of LBNO would consist of a deep underground laboratory hosting a magnetised iron calorimeter (MIND [3]) and the Giant Liquid Argon Charge Imaging ExpeRiment (GLACIER [4, 5, 6]). Thanks to its adjustable gain GLACIER can conduct experiments over a wide energy spectra ranging from the sub-GeV to multi-GeV. Therefore in addition to serve as LBNO far detector, GLACIER will adress a broad spectra of fundamental physics topics including proton decay search and astrophysical neutrino detection. GLACIER while being the key feature of LBNO is also its greatest technological challenge and requires intensive R&D and prototyping efforts.

## 2. Towards large area charge readouts

In the double phase LAr-TPC concept the ionisation charge is extracted to the Argon gas phase where it is amplified by a Large Electron Multiplier (LEM) which triggers Townsend multiplication in the high electric field regions in the LEM holes [7]. The electrons are efficiently extracted from the liquid with an electric field of around 2 kV/cm and amplified with a field of about 30 kV/cm applied across both electrodes of the LEM. The amplified charge is then collected and recorded on a two-dimensional and segmented anode. This principle has two main advantages: 1. the gain in the LEM is adjustable, i.e. the signal amplitude can be optimised, and 2. the signals collected on the two readout views are unipolar and symmetric which facilitates the event reconstruction. The double phase principle, was successfully demonstrated on a chamber equipped with a $10 \times 10$ cm$^2$ area readout (see e.g Refs. [8, 9] ) and more recently on a larger device consisting of a $40 \times 80$ cm$^2$ readout and 60 cm drift [10]. In the latter we reported on a stable operation at a constant gain of 15 corresponding to a signal to noise ratio of about 30 for minimum ionising particles. The possibility of having such large signal to noise ratios is very appealing, considering the fact that increasing detector sizes with longer drifts and larger readout capacitances lead to a degradation of the imaging quality of the device.

### *2.1. New 2D projective anodes*

In view of the extrapolation of the double phase technique to the large surfaces foreseen in GLACIER (typically one square meter), further R&D was conducted to simplify the design and reduce the electrical capacitance of the readouts. First, as explained in Ref. [11], we were able to extract the drifting electrons from the liquid to the gas by means of a single grid placed just below the liquid surface. We also designed and tested two dimensional projective readout anodes, manufactured from a single multilayer printed circuit board (PCB), leading to a reduction of the electrical capacitance of its electrodes. A picture along with an illustration of one of the anode is shown in Fig. 1. The 3 mm readout pitch of each view is segmented in two interconnected copper tracks which are printed on a multilayer PCB. The connections are made in such a way to preserve the $x - y$ symmetry of the anode. Thanks to this design, the anode offers a measured a capacitance per unit length of about 140 pF/m between neighbouring strips.

### *2.2. The experimental setup and definition of the gain*

In order to test its response, the anode was fitted to the so-called “3 liter” setup which is a double phase LAr LEM TPC consisting of a 21 cm long drift volume and a $10 \times 10$ cm$^2$ area. The setup has now been operated at CERN for more than 4 years, it is a well understood detector and very useful for testing new ideas with a rapid turn-around. A detailed description of the apparatus can be found in [12]. The chamber is exposed to cosmic muons tracks which are used to characterise the response of the chamber in terms of effective gain, signal-to-noise ratio and charge resolution. The crossing muons, once reconstructed in 3D[1], allow us to retrieve the length of the track on each strip of view 0 and view 1 ($\Delta s_0$ and $\Delta s_1$), along with the charge collected on the corresponding channels, $\Delta Q_0$ and $\Delta Q_1$ . The charge collected by unit

[1] All the analysis of the LAr data presented in those proceedings (noise filtering, hit-finding, track reconstruction, particle tracking in the case of simulated events etc..) is performed with the QScan software package [13].

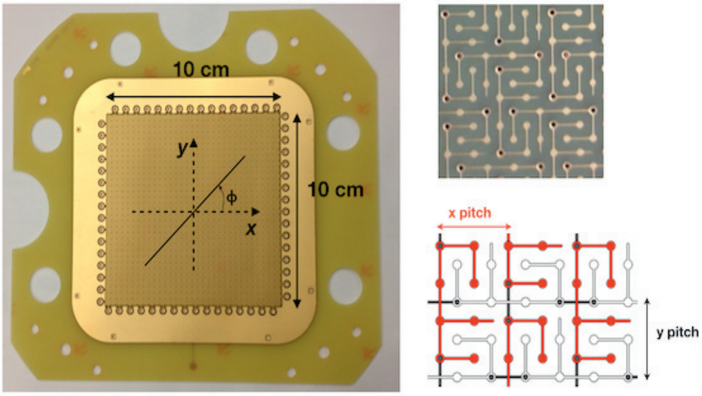


Fig. 1. *Left:* Picture of a 10x10 cm$^2$ multilayer PCB anode tested in our chamber with dimensions and coordinate system superimposed. *Right:* close up picture of the anode showing the copper track pattern that allows a 2 view readout on the same circuit board. A schematics explaining the interconnections between both views is also shown. The 3 mm readout pitches are indicated by arrows. View 0 is filled in red and view 1 in white.

length $\Delta Q_0/\Delta s_0$ and $\Delta Q_1/\Delta s_1$, which are proportional to the energy locally deposited by the track in liquid Argon, are the relevant quantities used to evaluate the performance of the anode and estimate the gain of the chamber. Since the cosmic muons that cross the chamber are minimum ionising particles (MIPs) the average charge deposition along a track, predicted by the Bethe-Bloch formula and accounting for electron-ion recombination [14] is $\langle \Delta Q/\Delta s \rangle_{MIP} = 10$ fC/cm. By using the sum of the collected charge per unit length on both views we hence define the effective gain by:

$$G_{eff} = \frac{\langle \Delta Q_0/\Delta s_0 \rangle + \langle \Delta Q_1/\Delta s_1 \rangle}{\langle \Delta Q/\Delta s \rangle_{MIP}} \tag{1}$$

$G_{eff}$ takes into account the charge multiplication in the LEM holes, as well as potential charge reduction from the liquid-vapour extraction efficiency and from the transparency of the grid and the LEM.

### 2.3. Uniformity of the charge collection

One of the important requirements of the anode is that the charge is efficiently shared between both views. Moreover the design should ensure that the response in terms of charge collected per unit length is independent of the angle at which the track crosses the strips. This is demonstrated in Fig. 2: the left plot shows the collected charge per unit length on view 0 ($\Delta Q_0/\Delta s_0$) as a function of the track azimuthal angle $\phi$ (see Fig. 1). As can be seen from the projections (middle plot) the $\Delta Q_0/\Delta s_0$ distributions are close to a

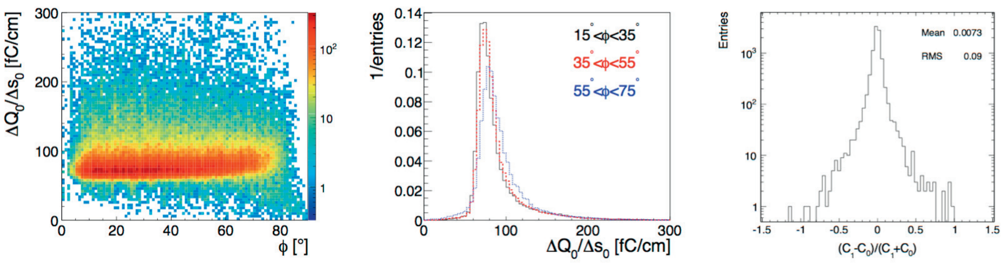


Fig. 2. Charge deposition measured on view 0 ($\Delta Q_0/\Delta s_0$) as a function of the track angle $\phi$ (left) and projection of the $\Delta Q_0/\Delta s_0$ distribution in three $\phi$ intervals (middle). The right plot shows the distribution of the difference between the total charge collected on both views normalised to their sum.

Landau function as expected from the fluctuations of the collected charge per unit length. The width and mean value of those distributions are also similar for all angular intervalls illustrating a uniform response. To illustrate the charge sharing between both views the right plot shows the distribution of the difference between the total charge collected on both views normalised to their sum. The distribution has an RMS of 9% and is centered around 0.7% indicating that the anode is indeed perfectly $x-y$ symmetric and that the charge is equally shared between both views. Many other anodes with alternate geometries were also tested. Their designs and the results are presented elsewhere [11]. The goal is always to reduce the capacitance per unit length without degrading the imaging capabilities of the TPC. From that point of vue, the one discussed here offers the best performance.

### 2.4. Long term stability of the gain

To quantify the long term stability of the gain, we observed the evolution of the gain over a period of about one month. All the electric fields were kept at the constant values listed in Table 1. During this period data was collected almost continuously, without any changes in the settings and without opening the chamber. The data acquisition was interrupted three times for a few days in order to purify the liquid Argon (see [12] for a description of the detector purification).

| | distance [mm] | electric field [kV/cm] |
|---|---|---|
| Induction (anode-LEM) | 2 | 5 |
| Amplification (LEM) | 1 | 33 |
| Extraction (LEM-grid) | 10 | 2 |
| drift (grid-cathode) | 210 | 0.5 |

Table 1. Electric field configuration

The evolution of the measured ionisation charge per unit length from view 0 ($\Delta Q_0/\Delta s_0$) over the entire period and corrected for the electron lifetime is shown in Fig. 3. The three purification periods, during which no electric field was applied across the LEM are removed from the graph. The effective gain is seen to stabilise after an initial decrease which is attributed to the electrostatic charging up of the dielectric medium of the LEM during operation. We find that the evolution of the effective gain is well described by the following empirical formula:

$$G_{eff}(t) = G_\infty \times 1/(1 - e^{-t/\tau}) \quad (2)$$

where $\tau$ is the characteristic charging-up time. A fit to the data points gives a gain which stabilises at $G_\infty \approx 15$ after an initial decrease with a characteristic time of $\tau \approx 1.6$ days. The six blue lines indicate the times at which discharges occurred across the LEM. While it is clear from the figure that those discharges do not disturb the evolution of the overall gain, locally the gain is affected in the region where the discharge occurred as shown in Fig. 4. Once a discharge occurred across a LEM hole, the initial gain is recovered over a region of about 1 $cm^2$ around the hole. The locally recovered gain then decreases with a similar time constant of one and a half days which supports the hypothesis that the effective gain reduction is a consequence of the charge accumulation on the dielectric of the LEM.

The signal-to-noise ratio for minimum ionising tracks is defined as the mean amplitude of the waveforms produced by the cosmic tracks divided by the average value of the noise RMS. Given our noise value of about 4-5 adc counts RMS and with the effective gain $G_\infty \approx 15$, the chamber is in a stable operation mode with a S/N $\approx 60$ for minimum ionising particles. Further studies will be conducted to check whether the chamber can be continuously operated at larger LEM fields and if higher gains in stable conditions can be reached.

## 3. Future developments: the LBNO demonstrator at CERN

A mandatory milestone in view of any future long baseline experiment is a concrete prototyping effort towards the envisioned large-scale detectors. The next priority of the LBNO collaboration is therefore the construction of a double phase liquid argon prototype with an active volume of $6 \times 6 \times 6$ $m^3$ in order to

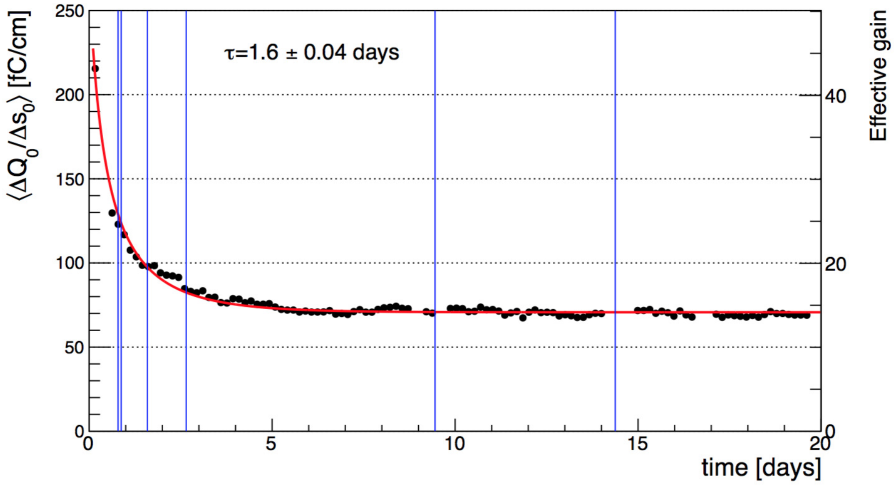


Fig. 3. Evolution of the effective gain corrected for pressure variations. The data points are fitted with the function $G_\infty \times \frac{1}{1-e^{-t/\tau}}$. The blue lines indicate the times at which discharges occurred.

demonstrate the technology at the relevant CLACIER scale. The detector will be situated in an extension of the CERN North Area hall and exposed to a charged particle beam from the SPS. A drawing of the detector is presented in Fig. 5, as well as a simulated 10 GeV $\pi^+$ event shot trough the beam pipe and initiating a shower in the liquid argon fiducial volume. The reconstructed hits of the event as a function of the drift time for both views are shown on the bottom display. The detector response including ionisation, drift and waveform generation is simulated with Qscan. The readout consists of 2000 strips for each view and the beam axis is orientated at 45° with respect to the strips to facilitate the event reconstruction.

Thanks to its very fine sampling the LAr TPC is known to deliver un-matched performance in terms of calorimetry and particle identification. In that respect, with the test beam campaign we plan to demonstrate the identification and reconstruction of electrons, charged pions and muons. We will also precisely quantify the electron / $\pi^0$ separation power in LAr which is of great importance to discriminate the $\nu_e$ charged current interactions from the neutrino neutral current interactions. All the collected data will be of great use to validate and improve existing reconstruction codes. A LAr TPC reconstruction software with a fully automatised reconstruction will be developed. Using charged particles with a well defined energy will also allow to study in detail the calorimetric response of this novel technology and precisely quantify the energy resolution in the range of the LBNO neutrino beam (typically between 0 and 10 GeV). All those measurements will provide important feedback on the estimates of the systematic errors linked to the detector performance and their impact on the LBNO physics programme.

Most importantly the prototype is at a relevant scale for testing and validating industrial solutions, to be employed for the GLACIER detector. From that point of vue some of the most urgent questions that will be adressed are:

i) *large area readout:* the 36 m$^2$ surface will be instrumented with the charge sensitive device providing gas amplification in ultra pure argon vapour. The charge readout device will consist of a top anode deck encompassing the extraction-grid and a large number (144) of individual LEM and anode modules. The deck is suspended via ropes passing through dedicated feedthroughs. A $1\times1$ m$^2$ mechanical mockup of the deck is currently under construction.

ii) *cold front-end electronics:* to maximise the signal-to-noise ratio cold front-end electronics are being developed so that the preamplifiers are located as close as possible to the charge-sensitive anode.

iii) *high voltage:* for a 1 kV/cm drift field the prototype requires 600 kV at the cathode (GLACIER with 20 m drift requires 2 MV). All the relevant structures, most importantly the cathode, field cage and

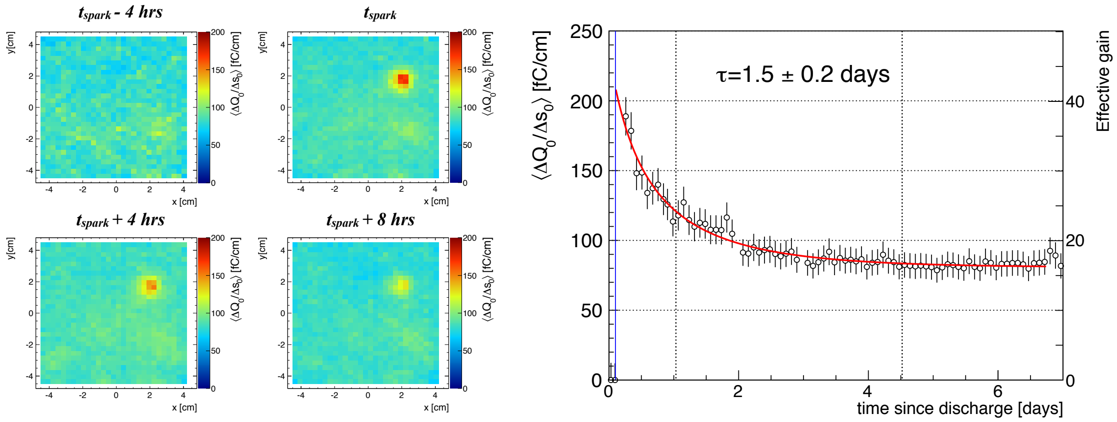


Fig. 4. *Left:* time evolution of $\langle \Delta Q_0/\Delta s_0 \rangle$ as a function of the $x-y$ coordinates. The plots are computed in intervals of four hours from top-left to bottom-right. A discharge occurred immediately before the second plot. *Right:* evolution of the maximum $\langle \Delta Q_0/\Delta s_0 \rangle$ amplitude in a 1 cm$^2$ area around the LEM hole where the discharge occurred.

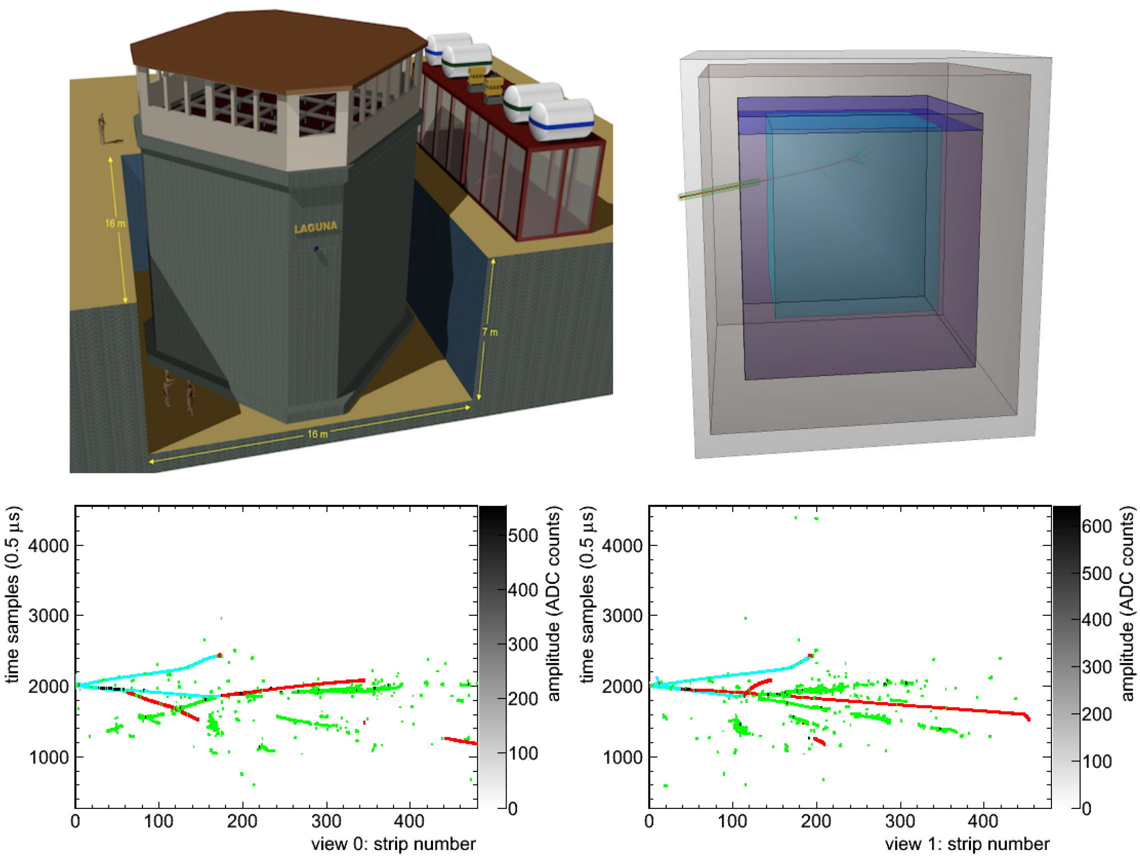


Fig. 5. *Top left:* 3D-CAD drawing of the LBNO prototype. *Top right:* Simulated 10 GeV/c $\pi^+$ event through the beam pipe. *Bottom:* drift time versus channel number of the reconstructed hits on both views. The hits are coloured according to the particle type: charged pions in cyan, $e^\pm$ in green and protons in red.

feedthroughs, should be able to withstand large potential differences. Concerning the breakdown voltage of liquid argon a dedicated R&D is under way at CERN. Preliminary results summarised in [15] show a rigidity larger than 100 kV/cm in stable (i.e non-boiling) liquid Argon.

iv) *purity:* this will be the first test with a large scale non-evacuable prototype and the same tank construction technique foreseen for the far detector.

A large number of those technical challenges are being adressed in conjunction with specialised engineering companies which have been mandated as part of LAGUNA-LBNO. A full Technical Design Report of the prototype will soon be delivered to CERN.

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## 4. Conclusion

LBNO has unique physics potential and takes full advantage of the LAr-TPC technology to explore the $L/E$ behaviour of the oscillated $\nu_\mu$ and $\bar{\nu}_\mu$ spectra. In that respect, GLACIER thanks to its high signal-to-noise ratio, excellent energy resolution, good granularity and large mass is a very attractive far detector. The technology has already been demonstrated on small scale prototypes and we now plan to prove the feasibility of double phase readouts on larger chambers. In that respect the most recent developments have shown encouraging results: we have manufactured printed circuit board anodes with readout strips that have a capacitance per unit length below 200 pF/m which means that the anode can be scaled to the square meter level without compromising the signal-to-noise ratio. We showed that the electrons can be efficiently extracted from the liquid to the gas phase by means of a single grid placed in the liquid. We operated a chamber newly equipped with the printed circuit board anode and the single extraction grid continuously for about a month with very few discharges across the LEM. The gain which initially decreases with a time constant of about 1.6 days remains constant at about 15.

All these considerations are important milestones towards the $6 \times 6 \times 6$ $m^3$ LBNO demonstrator. In addition to test the double phase principle on large volumes the prototype will provide very important and vital feedback not only for LBNO but also for long baseline programmes, and in general for the field. It will represent a so far never-achieved milestone for liquid argon detectors.

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