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Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC

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ABSTRACT: The ICARUS T600 detector, the largest liquid Argon Time Projection Chamber (LAr-TPC) realized after many years of R&D activities, was installed and successfully operated for 3 years at the INFN Gran Sasso underground Laboratory. One of the most important issues was the need of an extremely low residual electronegative impurity content in the liquid Argon, in order to transport the free electrons created by ionizing particles with very small attenuation along the drift path. The solutions adopted for the Argon recirculation and purification systems have permitted to reach impressive results in terms of Argon purity and a free electron lifetime exceeding 15 ms, corresponding to about 20 parts per trillion of O_2-equivalent contamination, a milestone for any future project involving LAr-TPCs and the development of higher detector mass scales.

KEYWORDS: Charge transport and multiplication in liquid media; Neutrino detectors; Cryogenic detectors; Time projection chambers

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Contents

1 Introduction

The innovative liquid Argon Time Projection Chamber (LAr-TPC) detection technique, proposed by C. Rubbia [1], observes ionizing events in neutrino processes or other rare events with a performance comparable to the one of a traditional bubble chamber. The LAr-TPC is fully electronic, continuously sensitive and self-triggering. Operated at atmospheric pressure with a cheap and abundant cryogenic noble liquid, it offers both visual and calorimetric determinations of the recorded events. The operating principle is based on the fact that in highly purified liquid Argon (or Xenon) free electrons from ionizing particles can be efficiently 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 ICARUS Collaboration has developed the LAr-TPC technology from prototypal dimensions to the mass of almost 800 tons of liquid Argon with the so-called T600 detector [2], installed in the underground INFN-LNGS Gran Sasso Laboratory near Assergi. Its successful and extended operation has demonstrated the enormous potentials of this novel detection technique, developing a vast physics program [3–5] and the simultaneous observation of neutrinos both from the CNGS beam at a distance of 730 km from CERN and from cosmic rays.

As a fundamental requirement for the LAr-TPC performance, electronegative impurities (mainly O_2, H_2O and CO_2) must be kept at extremely low concentrations. This goal can be achieved with a continuous LAr recirculation system with UHV construction techniques and dedicated filters. For instance, a ~ 5 m free electron attenuation length, equivalent to 3 ms lifetime in an electric guide field of 500 V/cm requires the O_2-equivalent concentration as low as 100 parts per trillion (ppt).

Laboratory studies initiated around 1987 with remarkably long free electron lifetimes were followed by a gradual industrialization of the technique. Already in 2001, only 2 months after the beginning of the first surface test run of one half of the T600 (275 m^3) [2], an electron lifetime of 1.8 ms was observed. During 2009, the value of 21 ms was measured at the Laboratori Nazionali di Legnaro (INFN-LNL) [6], however on a much smaller scale (120 liters prototype with 38 kg active mass). More recently, in the three years of T600 underground operation at the LNGS, electron lifetimes constantly exceeding several ms were obtained. During the last part of this data taking, a free electron lifetime exceeding 15 ms has been achieved. The analysis method and the most recent results of the measurement of the LAr purity are here described.

2 The ICARUS T600 detector

The ICARUS T600 detector consists of a large cryostat filled with about 760 tons of ultra-pure liquid Argon and split into two identical, adjacent modules. A more detailed description can be found elsewhere [2, 3]. Each module houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode. A uniform electric field (E_{drift} = 500 V/cm) drifts ionization electrons with $v_D \sim$ 1.6 mm/μs velocity towards the anode, consisting of three wire arrays and a stereoscopic event reconstruction. A total of 53248 wires are deployed, with a 3 mm pitch, oriented on each plane at a different angle (0°, +60°, -60°) with respect to the horizontal direction. By appropriate voltage biasing, the first two wire planes (Induction1 and Induction2) record signals in a non-destructive way; finally the ionization charge is collected and measured on the last plane (Collection).

The electronics was designed to allow continuous read-out, digitization and independent waveform recording of signals from each wire of the TPC. The read-out chain is organized on a 32-channel modularity. Signals of the charge sensitive front-end amplifiers have been digitized with 10-bits ADCs with 400 ns sampling channels. The overall gain is about 1000 electrons for each ADC count, setting the signal of minimum ionizing particles (m.i.p.) to $\sim$ 15 ADC counts. The average electronic noise is 1500 electrons, compared with the $\sim$ 15000 free electrons produced by a m.i.p. in 3 mm, leading to a signal to noise ratio S/N $\sim$ 10. The gain uniformity has been measured with an accuracy of about 5%, determined by the uncertainties on the adopted calibration capacitances.

In order to determine the absolute position of the track along the drift coordinate, the measurement of the absolute time of the ionizing event provided by a conventional photo-multiplier (PMT) system detecting the prompt scintillation light in LAr has been combined with the information coming from the electron drift velocity.

One thermal insulation vessel surrounds the two modules: between the insulation and the aluminium containers a thermal shield is placed, with boiling Nitrogen circulating inside to intercept the heat load and maintain the cryostat bulk temperature uniform (within 1 K) and stable at 89 K. Nitrogen is stored in two 30 m^3 LN_2 reservoirs. The temperature is fixed by the equilibrium pressure in the tanks (2.1 bar, corresponding to about 84 K), which is kept stable in a steady state by a dedicated re-liquefaction system of twelve cryo-coolers (48 kW global cold power), thus guaranteeing the safe operation in a closed-loop.

To keep the electronegative impurities in LAr at a very low concentration level, each module is equipped with two gasseous Argon (GAr) and one LAr recirculation/purification systems [3, 7, 9]. Argon gas is continuously drawn from the cryostat ceiling and, re-condensed, drops into Oxysorb^{TM} filters and finally returns to the LAr containers. LAr instead is recirculated by means of an immersed, cryogenic pump (~ 2 m^3/h [3], full volume recirculation in 6 days) and is purified through standard Hydrosorb^{TM} / Oxysorb^{TM} filters before being re-injected into the cryostats. LAr is extracted at 1.5 m from the floor on one side of the vessel, purified and injected back at the opposite longitudinal side (20 m apart) through several nozzles uniformly distributed close to the floor of the vessel. Convective motions induced by heat losses from the module walls ensure a fast and almost complete LAr mixing, minimizing the fluctuations of the relevant parameters, such as LAr density, temperature and purity.

3 Determination of the free electron lifetime in LAr

The electron lifetime $\tau_{\rm ele}$[1] in LAr-TPC has been measured with the help of the attenuation of the charge signal of traversing cosmic-ray muon tracks as a function of the electron drift distance.

A new precise method is here introduced to measure the attenuation $\lambda = 1/\tau_{\rm ele}$ of the actual ionization charge signal produced by the particle energy deposition in the ICARUS T600 events, as a function of the drift distance from the wire planes. An automatic procedure based on the recognition of the track pattern has been used to provide a first pre-selection of candidates for the purity measurement. An example of a muon track is shown in figure 1.

The charge signals have been measured in the Collection plane, removing channels with a r.m.s. noise exceeding 3 ADC counts (3000 electrons, twice the average noise). In order to provide a precise estimate of the signal attenuation only events with a track with > 100 wires and > 94 cm along the drift coordinate (corresponding to a drift time larger than 600 μs) have been selected. Tracks with evident associated electromagnetic showers, with large number of delta-rays, tracks interrupted by noisy wires and events with multiple tracks have been rejected. About 20% of the muon tracks survive these criteria.

The ionization charge is measured by the area of the signal pulse above the local baseline level. Single delta rays emitted at large angle along the track are removed by a recursive linear fit of the track (wire number versus the drift time), if at more than 3 mm distance from the track. As the result of these procedures, surviving tracks have on the average about 200 points.

A reliable fit of the charge attenuation along each track requires Gaussian-like distributions. This can be achieved truncating the asymmetric Landau tail of the dE/dx depositions, making the distribution more symmetric around the most probable value. However, to obtain a precise determination of the charge attenuation it is necessary to apply the truncation method uniformly along the track. The procedure is here elucidated in more detail.

As a first step the fitting procedure is applied to each track splitting it into shorter (~ 10) equal length segments in which the attenuation is negligible compared to the Landau fluctuations. Inside each segment the upper and lower 10% of the signals are discarded to mitigate anomalous fluctuations in the energy deposition, while retaining enough statistics. Then the provisional attenuation value is determined averaging over a track sample for which the LAr purity is not expected to vary appreciably (typically of the order of 100 tracks collected during half a day).

[1] Free electron lifetime is the average capture time of a free ionization electron by an electronegative impurity in LAr. This physical parameter depends in principle on the electric field since above 200 V/cm the drift electrons have more than thermal energy and their cross section for capture can therefore depend on the field. In this paper the free electron lifetime refers to the measurement at the nominal electric field of 500 V/cm in the ICARUS T600.

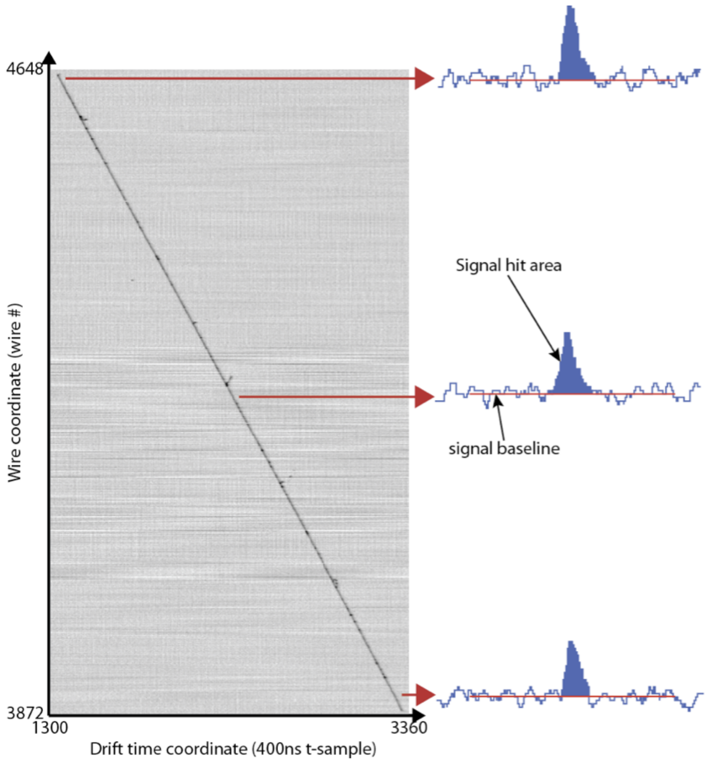

Figure 1. Example of a track used for purity measurement extending over 776 wires and 2060 t-samples, corresponding to a drift time of 824 μs. Signals of three different hits are also shown.

As a second step and following the attenuation value of the first iteration, the truncation method is applied to each track without any segmentation, applying a 30% upper Landau like cut and excluding the lower 1% of the signals. This procedure guarantees a signal distribution centered around the most probable dE/dx value; its correct application on the data is demonstrated by the observed uniformity of the truncation method along the track as shown in figure 2. A linear fit of the logarithm of the survived hit areas versus drift time along the whole track provides the estimation of attenuation λ_T associated to the selected track (figure 3).

The resulting distribution of the signals from single wires due to the above described truncated Landau distribution with the inclusion of the modest effect of electronic noise has an observed r.m.s. width $\sigma_i \simeq 14\%$ in agreement with previous estimations [4] (see figure 4).

The signals for single wires are then combined into tracks. As shown in figure 5, the observed r.m.s. width σ_λ of the λ_T distribution is $\sigma_\lambda \simeq 0.07$ ms^{-1}, unaffected by the actual λ_T, as verified experimentally for λ_T up to 1 ms^{-1}. This result is in rough agreement with the naively expected value $\sigma_\lambda \simeq \sqrt{(12/N)}\ \sigma_i/\Delta\mathrm{T} \simeq 0.05$ ms^{-1}, indipendent from λ_T and obtained combining the r.m.s. noise of the single wires ($\sigma_i \simeq 14\%$), the average number of hits along the track (N $\simeq$ 190) and the average drift time interval (ΔT $\simeq$ 0.70 ms). The comparison between the λ_T obtained in the first and in the second step is also shown in figure 6: the application of the second step in the method allows to obtain a better removal of the Landau tail of the dE/dx distribution and so a better fit of the logarithm of the survived hit areas versus drift time, producing a sizable reduction of the observed r.m.s. width of the λ_T distribution.

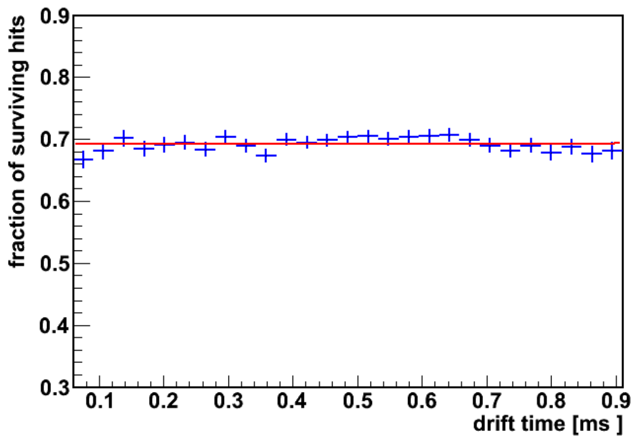

Figure 2. Fraction of surviving hits after the truncation method application as a function of the hit drift time. A sample of about 500 muon tracks has been studied.The linear fit (continuous line) is fully compatible with a uniform fraction of surviving hits along the drift time (slope: 0.0018 ± 0.01 ms^{-1}).

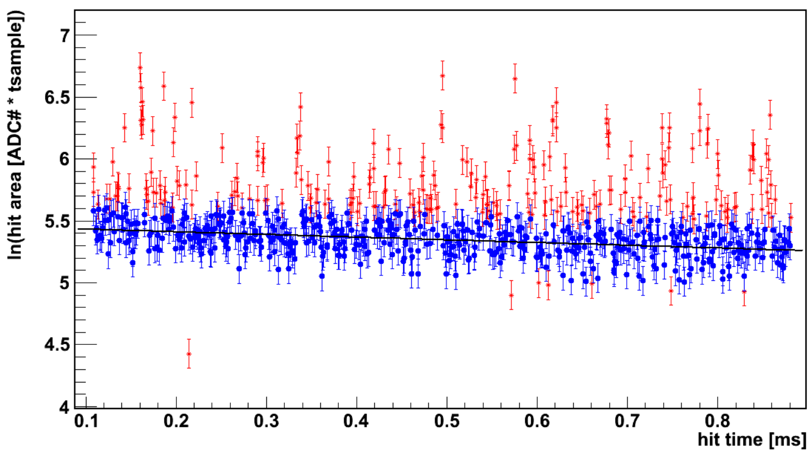

Figure 3. Pulse hit area as a function of the drift time for the track shown in figure 1; in red star the ~ 230 hits that are removed by the truncation method, in blue circle the ~ 510 surviving hits. The linear fit of the logarithm of the hit signal vs. drift time used to extract the electron signal attenuation is also shown (black line): for this event $\lambda_T = (0.212 \pm 0.022)$ ms^{-1}.

As an example for an event sample of ~ 100 tracks (corresponding to about half a day of data taking), the error on λ is 0.007 ms^{-1} allowing to reach a sensitivity on the electron attenuation length of 0.018 ms^{-1} at 99% C.L. In terms of free electron lifetime, this implies that values up to 20 ms can be precisely measured in such a relatively short time interval of data taking.

4 Experimental measurement of the lifetime

The through going cosmic rays collected at the rate of ~ 3100 muons per day have been used to measure the free electron lifetime in the ICARUS-T600 providing an almost ideal source of continuous calibration. The LAr purity trend in the T600 East module (figure 7) is here shown for

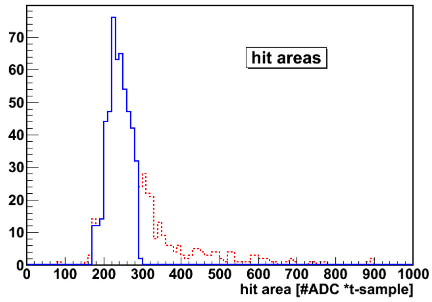

Figure 4. Landau distribution of the hit areas corrected by the charge attenuation (dotted line) for the muon track in figure 1; the effect of the truncation procedure is also shown (continuous line); the r.m.s. of the truncated distribution for this muon track is $\sim 12\%$.

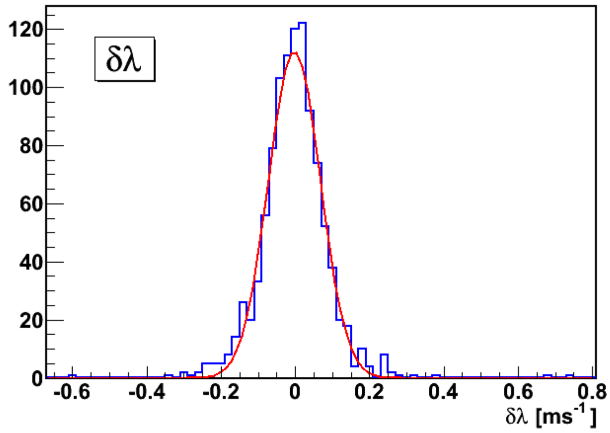

Figure 5. Distribution $\delta\lambda_T$ defined as the difference between the single-track λ_T measurements and the corresponding average value. The mean value and the width of the distribution obtained from the gaussian fit are (-0.0029 $\pm$ 0.0022) ms^{-1} and (0.07$\pm$ 0.002) ms^{-1} respectively.

the last few months of operation; each data point and the related errors are obtained averaging over $\sim$ 100 muon tracks collected in about half a day.

The analysis of the LAr purity demonstrates that the ICARUS detector has operated correctly only when both circulation systems are operational. The interruption of the liquid recirculation system for pump maintenance resulted in a rapid decrease of the electron lifetime that was restored promptly as the recirculation system was reactivated.

In April 2013 a major upgrade of the LAr recirculation system was performed in the East cryostat [7–9]. The ACD CRYO pump used during the first 2 years of run was replaced with a new Barber Nichols BNCP-32C-000 with an external motor similar to the ones used in the LN_2 circuit, which worked in a very efficient and reliable way without frequent stopping. During the 2 week stop of the LAr recirculation, required for the new pump installation, τ_{ele} rapidly decreased below 1 ms. After the new pump was switched on, the electron lifetime started increasing at a rate faster than before (see figure 7). At the end of the ICARUS data taking the electron lifetime was still rising and the last measurement before the detector stop resulted to be $16.1^{+1.3}_{-1.1}$ ms corresponding to a maximum signal attenuation of 6% at 1.5 m drift distance. The remarkable LAr purity obtained

2014 JINST 9 P12006

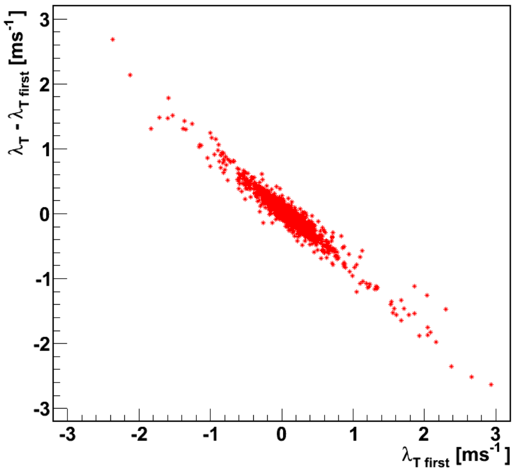

Figure 6. Scatter plot of the λ_T-λ_{TFirst} against λ_{TFirst}, where λ_{TFirst} is the measurement obtained for the track in the first step: the visible strong anti-correlation demonstrates that the second step results in an improvement of the λ_T measurement, producing a sizable reduction of the observed width of the λ_T distribution.

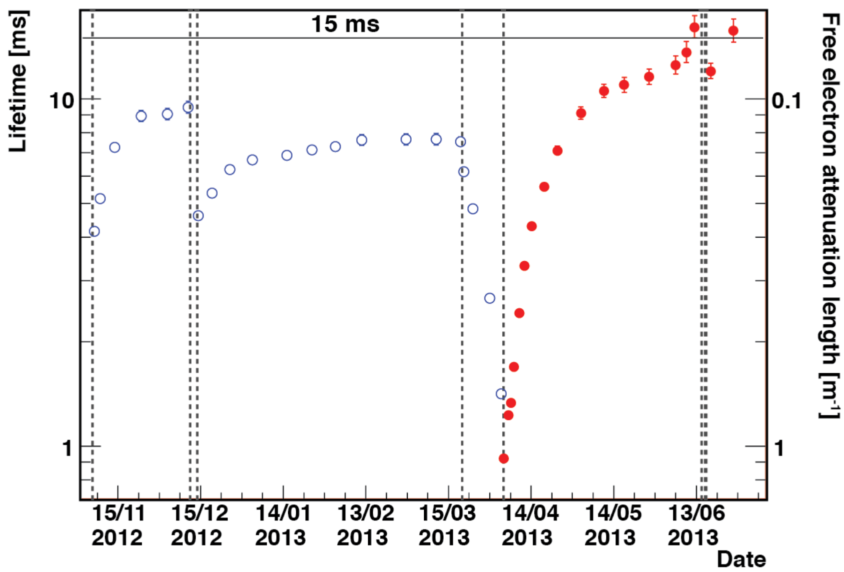

Figure 7. Electron lifetime τ of the East module for the last part of the ICARUS data taking: in red full points the measurements with the new pump with external motor are shown. The dashed vertical lines represent the stops and restart of the LAr recirculation; during this period the GAr recirculation system continued to operate.

in the large T600 detector approaches the result of τ_{ele} = 21 ms previously obtained with the smaller LAr-TPC prototype of INFN-LNL [6].

In view of the very large dimensions of the detector, the uniformity of the observed lifetime over the volume is a crucial element that has to be demonstrated. The level of accuracy achieved for

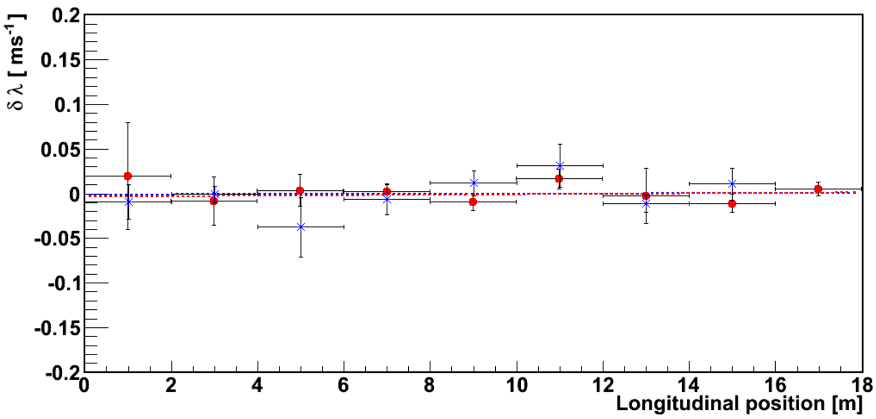

Figure 8. The measured variation of the level of impurities in the East cryostat along the longitudinal direction. Red circles refer to the left chamber, blu stars to the right one. The dashed lines are the linear fits in both chambers. The fit results are amply compatible with a uniform LAr purity across the length of the whole detector: slope for the left chamber $(8.8 \pm 90) \cdot 10^{-5}$ ms^{-1}m^{-1}, slope for the right chamber $(2.7 \pm 11) \cdot 10^{-4}$ ms^{-1}m^{-1}.

the charge attenuation measurements along single muon tracks allows estimating the uniformity of the LAr purity in different regions along the 20 m detector length. To achieve uniformity, as already pointed out, in each cryostat the injection of the LAr is located at one side ~ 2 m below the surface and the extraction at 20 m apart at the opposite side.

In order to investigate the uniformity of the lifetime along the detector, a sample of 1000 almost vertical cosmic muon tracks in the East cryostat have been selected in different periods over the last 2 months of the ICARUS data taking in which the signal attenuation was $0.06 < \lambda < 0.10\,\mathrm{ms}^{-1}$. The tracks have been automatically reconstructed in 3D in order to define their position along the detector longitudinal direction, which has been divided in 9 regions of 2 m each both for the left and the right chamber. For each region, the distribution of the $\delta\lambda$ parameter, defined as the difference between the λ_T associated to the track and the λ value measured in the considered period, has been determined and the mean value for the tracks inside the selected 2 m region has been extracted. The trend of the $\delta\lambda$ parameter as measured along the longitudinal direction of the cryostat (figure 8) shows a complete uniformity of the LAr impurities: indeed the linear fit of $\delta\lambda$ presents a slope compatible with zero within one sigma in both chambers. A similar behaviour has been observed also in a period during which the LAr purity was rapidly increasing from 3.3 ms to 5.6 ms. These results are in agreement with the assumption that convective motions in the T600 detector are sufficient to mix LAr faster than the typical recirculation time (6 days), thus minimizing any fluctuations of the electron lifetime within the detector volume.

5 Independent verifications of the results

5.1 Muons from neutrino events

The LAr purity measurement method was validated applying the attenuation λ measured with the cosmic muons to an independent sample of muon tracks from CNGS neutrino interactions in the

2014 JINST 9 P12006

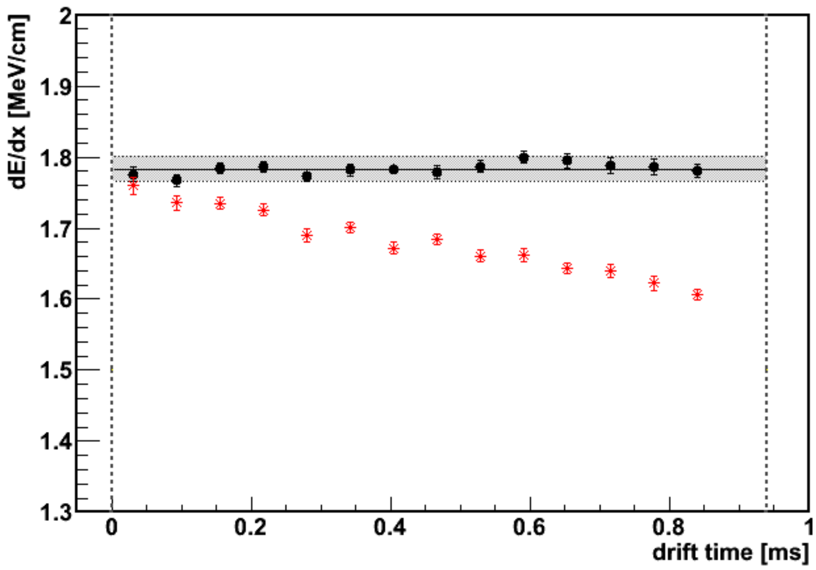

Figure 9. The average of the reconstructed most probable value of dE/dx for a sample of CNGS muons is shown as a function of the drift coordinate before (red stars) and after (black points) the correction for the measured $\lambda = 1/\tau_{ele} = 0.11\ \text{ms}^{-1}$. Only the statistical errors are given. The residual 1% systematic uncertainty band is also shown to guide the eye.

upstream rock collected in the same period of time. In the considered data sample the electron lifetime was measured to be between 8.8 and 9.5 ms, quite stable within the measurement errors.

The 254 selected CNGS muons, entering the T600 module and travelling almost parallel to the wire planes, have been automatically reconstructed in 3D [10] and the dE/dx associated to each hit along the track has been estimated as well as the related position along the drift. The drift path has been split into 15 bins of 10 cm each and the last bin has been discarded due to small electric fields distortions in the cathode region. For each event, the dE/dx distributions are constructed for every drift bin, requiring at least 30 entries per bin to extract the most probable dE/dx value by fitting the charge signal distribution with the convolution of Landau and Gaussian functions. The most probable value of the energy loss has been preferred to the average energy loss because of its negligible dependence on muon momentum in the CNGS energy range. The available event statistics allows achieving in all the 15 bins a statistical precision better than 1%.

As a result, the average dE/dx of the analyzed CNGS tracks, corrected by the λ measurement, is independent from the drift coordinate within the errors, demonstrating the reliability of the LAr purity estimation method (figure 9).

5.2 Monte Carlo events

The above described method for the purity measurement has been tested on a 9000 muon track sample in the T600 LAr-TPC generated with the energy spectrum and the angular distribution of cosmic rays measured at LNGS by a dedicated Monte Carlo program based on the FLUKA code [11, 12]. The simulation includes the free electron longitudinal diffusion, the electronic response and the noise measured in the detector as well as the signal attenuation due to the impurities in LAr [2].

2014 JINST 9 P12006

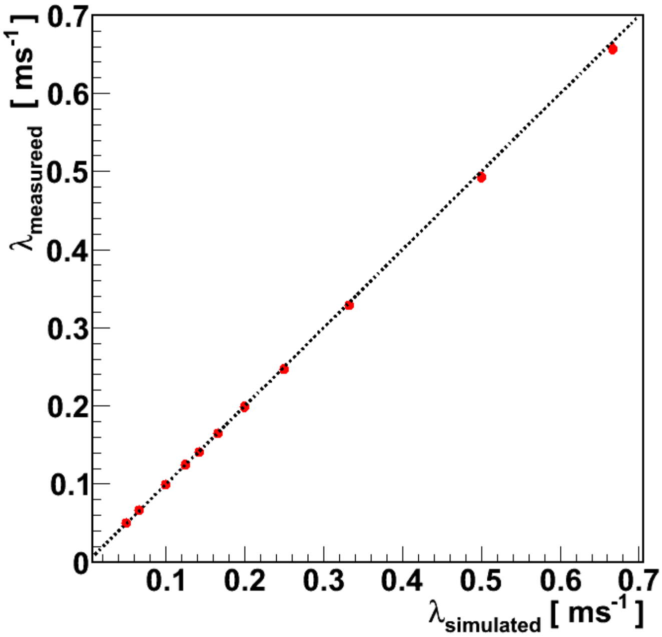

Figure 10. The signal attenuation λ as measured with the Monte Carlo events as a function of the simulated attenuation values. A small difference is visible, however well within the measurement errors. The interval of λ corresponds to an electron lifetime between 1.5 and 20 ms.

The method has been tested for electron lifetime in the 1.5 - 20 ms interval focusing in particolar on the cases in which the expected attenuation is relatively small (e.g. a $\sim 10\%$ signal attenuation for the maximum drift length is expected for $\tau_{\rm ele} \sim 10$ ms). According to the described selection criteria, about 2000 simulated tracks were retained as candidates for LAr purity measurements.

The observed r.m.s. width σ_λ of the electron attenuation λ_T distribution in the MC events is $\sigma_\lambda \simeq 0.06\ \text{ms}^{-1}$, in a reasonable agreement with experimental results (figure 5). The results of the presented method applied to simulated data at different purity values, summarized in figure 10, show the measurement reliability in a large range of LAr purity values. The residual $< 1\%$ underestimation of λ at LAr high purity values ($\tau_{\rm ele} > 3$ ms) corresponds to $< 0.3\%$ effect on the charge signal corrected for the attenuation effect even for the maximum drift time of 1 ms. For low purity values ($\tau_{\rm ele} < 3$ ms) a $\sim 1.5\%$ underestimation is detected affecting the charge signal correction less than 1%.

6 Conclusions

The successful ICARUS-T600 operation at LNGS with the simultaneous exposure to both CNGS neutrino beam and cosmic rays, demonstrates the enormous potential of this detection technique. The ICARUS cryogenic system and the solutions adopted for the argon re-circulation and purification systems permitted to reach an impressive result in terms of argon purity, which is one of the key issues for the superb detector performance. A corresponding free electron lifetime exceeding 15 ms has been obtained corresponding to a mean attenuation length of 25 meters, a milestone for any future project involving liquid argon TPC.

2014 JINST 9 P12006

In addition this result demonstrates the effectiveness of the single phase LAr-TPC detectors paving the way to the construction of huge detectors with longer drift distances: for example, with the achieved purity level, at 5 m from the wire planes the maximum signal attenuation is only $\sim 23\%$.

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