ICARUS — THE LIQUID ARGON DETECTOR FOR NEUTRINO PHYSICS* **

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This article describes shortly the Liquid Argon TPC detection technique used in ICARUS experiment and discusses the results of tests of the ICARUS detector. Some future prospects of LAr TPC technique are also presented.

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1. Introduction

ICARUS (Imaging Cosmic and Rare Underground Signals) is an international experiment aimed at proton decay search and studying interactions of atmospheric, solar and beam neutrinos. It consists of modules placed in the underground laboratory in Gran Sasso, in central part of Italy, near l'Aquila. It is a Time Projection Chamber (TPC) filled with liquid argon. The technique used for detection combines the characteristics of a bubble chamber with advantages of electronic readout.

2. The Liquid Argon TPC Technique

A halfmodule (T300) of the detector is an aluminium box (3.6m wide, 3.9m high, 19.9m long) — a cryostat — filled with 300 tons of liquid argon. A cathode is placed in the middle to sustain an electric field inside. Three anode wire planes are installed along the sidewalls of the detector — they serve as a readout equipment. A wire plane is a plane of multiple parallel wires, with a distance between consecutive wires of 3 mm. Wires on each plane are oriented in different directions (*i.e.* $-60, 0, 60$ degrees with respect

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to the bottom of the detector). Several photomultipliers are also mounted on the walls. The detailed description of ICARUS modules is given in [1]. The detector is capable of recording tracks of charged particles traversing the active liquid argon volume. Every such particle ionises the medium and produces electron-ion pairs. The electrons are then transported towards the sidewalls by a uniform electric field present inside the detector. Electrons reaching the wires are recorded by all three planes — they induce signals on the first two planes (called *Induction planes*) and are collected on the third plane (*Collection plane*). The signal from the wires in each plane can be presented as a two-dimensional image with one dimension being the wire number, and the other the time of flight of ionisation electrons. To properly calculate this time, a triggering mechanism is provided — the particles also produce fast scintillation light, which is recorded by the photomultipliers. The detector is therefore continuously sensitive and self-triggering.

Since the wires on each plane are oriented in different directions, the images obtained are different projections of events inside the detector. This allows for spatial reconstruction: one can take advantage of having three different views of the same event. The first step of the procedure is the hit identification in 2D images. A hit is a point of a track in 2D image. Then adjacent hits are grouped into larger structures, called clusters. Reconstruction ends with finding corresponding clusters in three projections and this way obtaining their position in space. Using this technique one can achieve a very good spatial resolution of $3\times3\times0.6mm$ (the most precise measurement is given by the time of flight coordinate).

The charge of electrons collected on the Collection plane is proportional to the ionisation energy loss of the particle traversing the detector. Information from the Collection plane is therefore used for calorimetric reconstruction. The total energy of a particle can be reconstructed this way only if the track in question is fully contained in the volume of the detector; for long tracks exiting the detector, a more suitable method utilizes multiple scattering analysis. The particle identification is based on examining the energy loss pattern of a particle.

3. Test run in Pavia

A single halfmodule of the detector was thoroughly tested in the summer of 2001 in Pavia (Italy). The tests were carried out on the surface of the earth and lasted over 100 days. The tests served as a proof of the concept: all technical aspects of the system were checked and some data were collected (mainly cosmic rays). Some of the images collected are shown in Fig. 1. Each image is a collection of signals from consecutive wires, with the horizontal coordinate corresponding to the wire number, and the vertical to drift time. The darker the pixels, the larger the signal. Events with long muon tracks traversing the whole detector length were also collected demonstrating the capabilities of DAQ system. One can now consider the liquid argon technology mature.

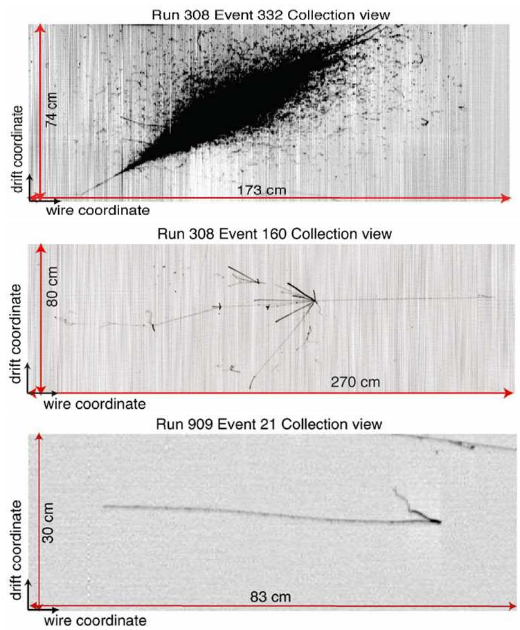

Fig. 1. Examples of events collected during the test run. From top to bottom: an electromagnetic shower, a hadronic interaction, a decaying muon [1].

Electron lifetime and drift velocity — essential for proper operation of the TPC and reliable reconstruction of events — were examined [3]. If $N_e(0)$ is the number of electrons produced in LAr at time $t = 0$, then one can expect to find a reduced number of electrons at time t, according to the exponential formula $N_e(t) = N_e(0)\exp(-\frac{t}{\tau_e})$, where lifetime τ_e is inversely proportional to the concentration of electro-negative impurities and electron attachment rate. The electron lifetime must be long enough to let the electrons travel at least 1.5m (the distance between the cathode and the sidewalls) in order to produce signals and, subsequently, reliable images of events inside the chamber. To achieve that, the impurities diluted in LAr must be reduced to a very low level by means of filtering. The finite lifetime of electrons should also be taken into account for proper calorimetric measurement. Fig. 2 shows the results of argon purity measurements during the test run. The measurements were carried out by means of two methods: by purity monitors and analysis of muon tracks. The plot shows that after some initial time, the electron lifetime corresponding to 1.5m of drift (ca 1ms) is easily achieved.

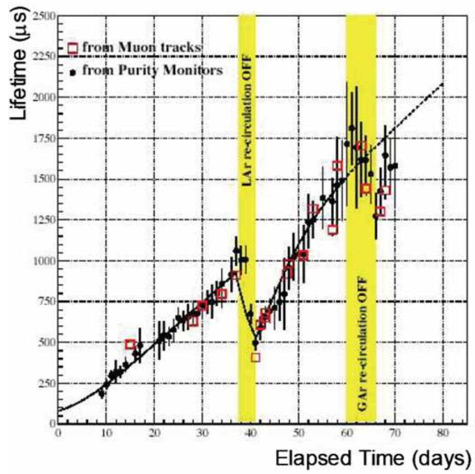

Fig. 2. Measured electron lifetime as a function of time of detector operation [3].

The electron velocity parameter is needed for proper calculation of drift coordinate. The velocity depends on the temperature of medium (it is constant and set at about 89K) and electric field applied. Fig. 3 shows the velocity as a function of electric field. The value of E of order of 0.4–0.5 kV/cm was chosen as a working region (corresponding to 1.4–1.6 m/ms).

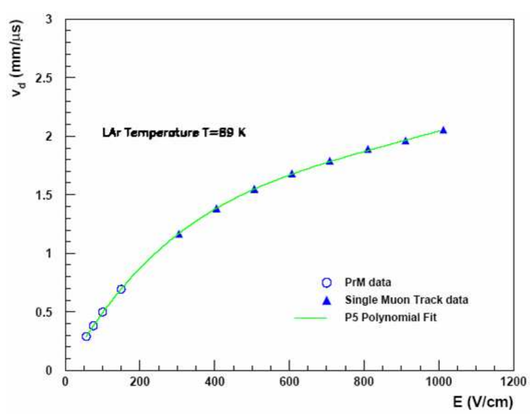

Fig. 3. Measured electron drift velocity as a function of electric field intensity [3].

Data from the test run were used to perform some physical analyses to test the capabilities of the detector. One of them was Michel spectrum measurement performed on a decaying muons data sample. Michel spectrum is the energy spectrum of electrons coming from decaying muons. One can find the resulting spectrum in good agreement with Standard Model expectations [2]. Some other analyses are in progress, including π^0 mass determination analysis. This is an important calibration test for electromagnetic component. The analysis is based on reconstruction of energy of gamma showers induced by a decaying pion. The results of this analysis are to be published soon.

4. Oscillation analysis

The presence of CNGS beam, which is to start its operation in 2006, would enable one to study $\nu_\mu \to \nu_\tau$ oscillations. In order to do that, one has to perform a ν_τ appearance analysis, selecting sufficiently large and pure sample of ν_τ events. A number of such studies were carried out. The selection of tau events was based on their topological properties associated with decay of tau lepton. Several methods were applied: from simple selection based on four variables to sophisticated searches by means of neural networks and maximum likelihood utilizing over 10 variables. The procedure was carried out in three different channels — with electron, with muon and without any charged lepton visible. The results for the electron channel are shown in Fig. 4. One can see that a very pure sample of ν_τ events can be obtained, with contribution from background at about 5 percent only [1]. The results for no leptons channel are also promising.

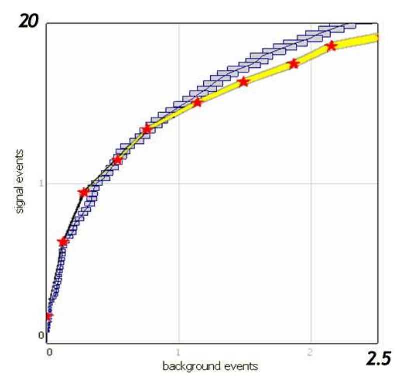

Fig. 4. ν_τ selection analysis results for 7.6 kton $\times$ year exposure. Bars denote neural network analysis results, while stars — maximum likelihood analysis results.

5. Future prospects of the technique

The development of LAr technique is now going in two separate directions: building small (100 ton) and large (100 kton) detectors. The projects discussed below are not part of ICARUS; nevertheless their development can be regarded as a consequence of successful testing of ICARUS detector.

5.1. Small detectors

Small LAr detectors are a good solution for near station detectors in long-baseline neutrino experiments. They can be used for cross-section measurement, flux determination, measurement of electron neutrino component and π^0 production. Introduction of such a detector is proposed in T2K experiment in Japan; small LAr module would serve as a supplement for water Cherenkov detector and muon ranger in the intermediate station of the experiment [4].

5.2. Large detectors

Large LAr detectors are designed for proton decay searches and high statistics studies of beam (possibly off-axis) and astrophysical neutrinos. They can help determining mass hierarchy, θ_{13} mixing angle and discover CP violation in the neutrino sector. Huge cryo-tanks necessary for such an experiment are used in petrochemical industry and are commercially available. Several designs of large LAr TPCs are considered: a bi-phase mode detector with gas amplification [4] and more conventional detectors, divided into several chambers containing liquid argon only [5, 6].

There are many proposed locations for detectors of this type, including Polkowice–Sieroszowice copper mines in Poland, which is a promising underground location due to low background and suitable environment (a cavern in a dry salt layer). Several locations in Italy are also taken into account.

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