

# The ICARUS detector. Past, present and future

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**Abstract.** ICARUS T600 is currently the largest LAr TPC built as a neutrino detector. During its operation in the underground LNGS laboratory, it has recorded events from the CERN to Gran Sasso neutrino beam and cosmic rays interactions. Thanks to its excellent imaging capabilities and very good calorimetric and spatial resolutions, several meaningful results have been achieved. This paper introduces shortly the observation of a free electron lifetime exceeding 15 ms, the identification of atmospheric neutrino interactions and the search of LSND-related anomalies in the  $\nu_e$  appearance from the  $\nu_\mu$  CNGS beam. The LSND anomaly will be further addressed by the Short Baseline Neutrino programme, carried out at the Fermilab laboratory. The ICARUS detector will be used as a far detector in this programme.

## 1. The ICARUS detector - single phase Liquid Argon TPC

The ICARUS T600 detector is a single phase Liquid Argon Time Projection Chamber (LAr TPC) with 760 t of total mass (476 t active mass). It was successfully operated in the LNGS underground laboratory in Italy, concluding its long operation run in 2013. During its operation, the data from the the CERN to Gran Sasso (CNGS) neutrino beam and cosmic rays have been collected. The LAr TPC technique allows to collect two kinds of signal: the ionization electrons at anode wires, and scintillation light by photomultipliers (PMTs). Using these two sources of signal, a three dimensional reconstruction of any ionizing particles crossing the detector is possible with a spatial resolution of about 1 mm<sup>3</sup>. This allows to analyse neutrino interactions in the broad range of energies and event topologies [1].

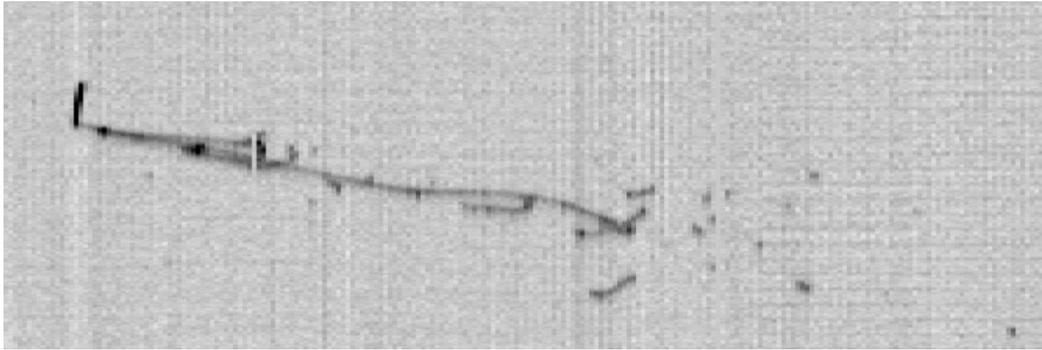
The ICARUS T600 cryostat consists of two identical modules. Each cryostat houses two TPCs with a common cathode placed in the middle. The maximum drift length of electrons is equal to 1.5 m. The 500 V/cm uniform electric field drifts electrons with the drift velocity  $v_d = 1.6$  mm/ $\mu$ s towards three-anode wire planes, 3 mm apart. Thanks to the carefully applied voltages, the signal is recorded in a non-destructive way by the first two Induction wire planes, whereas the ionization charge is collected on the third Collection plane. Arrays of PMTs placed behind wire planes detect fast scintillation light, providing the measurement of the absolute time of an event and suits as a trigger. Detailed description of the ICARUS T600 detector can be found in [2] and [3].

### 1.1. Purification of LAr and electron lifetime

The operation of LAr TPC requires a high purity of LAr the higher, the longer electron drift paths are needed. The presence of electron trapping polar impurities, most of all  $O_2$ , in the Liquid Argon produces an exponential attenuation of the electron signal along the drift coordinate. Therefore, argon must be continuously filtered and recirculated. The solutions used for the argon recirculation and purification systems in ICARUS, permitted to reach an extremely low level of electronegative





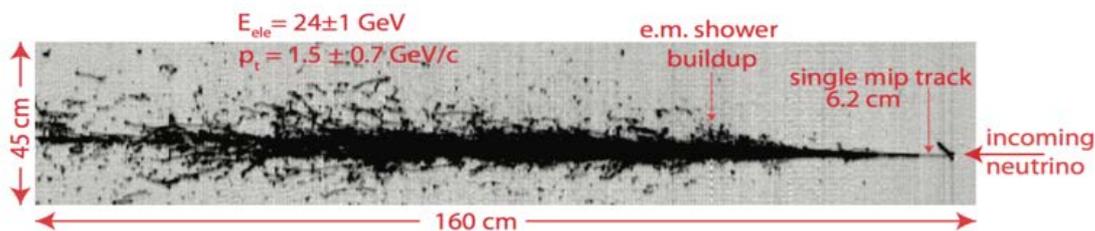


**Figure 2.** Example of identified atmospheric electron-like neutrino interaction. First segment of developing cascade comes from a single particle-electron. Total deposited energy was estimated as 240 MeV

### 3. LSND like anomaly search in CNGS beam

The LSND experiment observed an excess of anti- $\nu_e$  neutrino events in anti- $\nu_\mu$  beam which can imply the existence of a new additional sterile neutrino flavour. The anomaly was further studied by MiniBooNE experiment using both neutrino and antineutrino beam. The observed results were not fully consistent with expectations and therefore the anomaly not fully explained.

The ICARUS detector offers the possibility of an excellent electron vs.  $\gamma$  separation and therefore minimise the main source of background for e-like neutrino events coming from neutral current interactions with  $\pi^0$  production. The ICARUS Collaboration searched for electron neutrino appearance in the CNGS  $\nu_\mu$  beam in the context of LSND-like anomalies. The updated analysis based on 2,450 neutrino events, corresponding to the  $7.2 \times 10^{19}$  POT, is described in details in [6]. The dedicated search for electron neutrino event candidates in the detector fiducial volume from the CNGS beam, with an event energy less than 30 GeV, was performed. Six e-like events have been found, for an example see figure 3. The expected number of e-like events from known sources, like intrinsic beam contamination and standard three flavour oscillations, taking into account the selection efficiency as  $0.74 \pm 0.05$ , is equal to  $7.9 \pm 1.0$  (syst. error only) [6]. The result is compatible with the expectations within the standard theory. The analysis allowed to narrow down the limit on allowed values of sterile mixing parameters within 3 active  $\nu$  + 1sterile  $\nu$  model, however the anomaly needs further attention.



**Figure 3.** Example of one from six electron neutrino interaction from the CNGS  $\nu_\mu$  beam. First segment of developing cascade comes from a single minimum ionising particle ( $dE/dx < 3.1$  MeV)

### 4. The Fermilab Short Baseline Neutrino Program at Booster Neutrino Beam

The Short-Baseline Neutrino Program at Fermilab in USA emerged from a joint proposal by three collaborations [7]. The main idea was to use their detectors to perform sensitive searches for  $\nu_e$  appearance and  $\nu_\mu$  disappearance in the Booster Neutrino Beam (BNB), addressing the LSND anomaly and sterile neutrino oscillation hypothesis. All of the detectors use the technology of LAr TPCs - liquid argon time projection chambers.

ICARUS T600 detector will serve as the far detector placed at the distance of 600 m, farthest from the BNB primary target, giving the signal for the oscillation analysis of the Short Baseline program. ICARUS T600 is currently being refurbished at CERN. The updated electronics and light detection systems are being installed and tested. The T-600 detector will be moved to Fermilab and placed on the beam in 2017.

The MicroBooNE detector is already located 470 m from the BNB primary target. Its total mass equals 170 tons while active mass amounts to 89 tons of liquid argon. The cryostat was successfully filled in mid 2015 and the detector is currently running and taking data. The Short-Baseline Near Detector (SBND) will be located close to the BNB primary target at the 110 m distance. Its role will be to precisely measure the unoscillated neutrino flux and significantly reduce systematic errors on the prediction of an expected neutrino flux in the far site. Its fiducial mass is foreseen to be 82 tons. The cryostat technology will be produced according to one of the proposed solutions for future LAr TPC detectors foreseen in the long baseline neutrino programme LBNF-DUNE. The SBND detector is expected to be installed on the BNB beam in 2018.

The proposed SBND experiment will likely clarify LSND/MiniBooNE anomaly by precisely and independently measuring both  $\nu_e$  appearance and  $\nu_\mu$  disappearance oscillation channels. In case of absence of “anomalies”, the three detector signals should be a closer copy of each other for all experimental signatures. The sensitivity studies and MC simulations demonstrate the possibility to cover the LSND anomaly parameter region on the five sigma confidence level for excluding the sterile neutrino hypothesis, assuming the three years data taking by all three LAr-TPC detectors.

## 5. Conclusions

The ICARUS T600 detector, with 476 ton of sensitive mass, is the largest Liquid Argon Time Projection Chamber ever constructed representing the state of the art for this detection technology. The successful, continuous, long-term operation of ICARUS T600 has conclusively demonstrated that the single phase LAr TPC is the leading technology for the future neutrino experiments. Several examples of analysis results of collected data from various sources have been announced. At the end of 2014, ICARUS T600 detector has been transported to CERN for overhauling within the WA104 CERN neutrino program. The upgraded ICARUS T600 detector, together with MicroBooNE and SBND detectors form the Fermilab Short Baseline Neutrino programme dedicated to finding a solution to the observed short-baseline anomalies and the determination of the existence of the sterile neutrino.

## 6. Acknowledgments

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