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Upgrade of the ICARUS T600 Time Projection Chamber

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Abstract. The ICARUS T600 detector, with about 500 tons of active mass, is the largest Liquid Argon Time Projection Chamber (LAr TPC) ever realised. In 2013 ICARUS concluded an about 4 years long experiment with the T600 detector at the LNGS underground laboratory, taking data both with the CNGS neutrino beam and cosmic rays. This very successful experiment demonstrated the high spatial and energy resolutions, electron/photon separation and particle identification capabilities (via $dE/dx$ vs range measurements) of the LAr technology.

ICARUS Collaboration refurbished the T600 at CERN, in order to move it to FNAL in the framework of the SBN experiment, to serve as far detector in studies on the short baseline neutrino oscillations.

A fundamental part of ICARUS is the light collection system, made of 360 Hamamatsu R5912-MOD, 8 in. diameter, PMT’s. This system is dedicated to three tasks: the generation of a light based trigger signal, the identification of the time of occurrence ($t_0$) of each interaction with high time precision and the initial recognition of event topology for fast event selection purposes.

1. Introduction

ICARUS-T600 is an ideal detector for neutrino physics and search for rare events. It is a uniform, self-triggering detector, with high granularity ($\sim$ 1 mm), 3D imaging and calorimetric capabilities. It allows to accurately reconstruct a wide variety of ionizing events with complex topologies.

ICARUS is made of two identical modules, for a total of 476 t active mass. There are 2 LAr TPC’s per module (internal dimensions of each chamber are 3.6 (W) x 3.9 (H) x 19.6 (L) m), with a common central cathode generating an average drift electric field $E_D=0.5$ kV/cm (so the electrons have drift speed $v_D \sim 1.6$ mm/$\mu$s and 1.5 m drift length); 3 ”non-destructive” readout wire planes per TPC: $\approx 54000$ wires at $0^\circ, \pm 60^\circ$ with respect to horizontal direction, called respectively Induction 1, Induction 2 and Collection plane, when going outward from the cathode plane; 8” PMT’s arrays, used for time of occurrence $t_0$ signal, timing and triggering of events, sensitive at 128 nm LAr scintillation light via Tetra-Phenil-Butadiene (TPB) wavelength shifter on glass window. The ionisation charge is continuously read ($0.4$ $\mu$s sampling time). On average, $\approx 2 \cdot 10^4$ ionisation electrons are produced per MeV.
Exposed to the Cern Neutrino to Gran Sasso (CNGS) beam, ICARUS lasted in 2013 a very successful 3-year run at Gran Sasso INFN underground laboratory, collecting $8.6 \cdot 10^{19}$ pot event statistics with a detector live time > 93% and cosmic rays to study atmospheric neutrinos (0.73 kt y exposure). Several physics/technical results have been achieved during the run at LNGS: an exceptionally low level $\sim 20$ p.p.t. [O2] eq. of electronegative impurities in LAr; the measured electron lifetime $\tau_{\text{ele}} > 15$ ms ensured few meters long drift path of the ionising electron signal without attenuation; demonstrated the detector performance, especially in $\nu_e$ identification and $\pi^0$ background rejection in $\nu_\mu - \nu_e$ study to unprecedented level; performed a sensitive search for LSND-like anomaly with CNGS beam, constraining the LSND window to a narrow region at $\Delta m^2 < 1 eV^2$. These results marked a milestone for LAr-TPC technology with a large impact on future neutrino and astroparticle physics projects, i.e. the current SBN short base-line neutrino program at FNAL with 3 LAr-TPC’s (SBND, MicroBooNE and ICARUS) and the multi-kt DUNE LAr-TPC. T600 detector will be exposed to $\sim 0.8$ GeV Booster $\nu_\mu$ beam, 600 m from target to definitely test the LSND claim searching for $\nu_\mu - \nu_e$ oscillations in the framework of SBN program.

In 2015, T600 detector was moved from LNGS to CERN to introduce some technology developments while maintaining the already achieved performance. To face the new experimental situation at FNAL, ICARUS T600 underwent an intensive overhauling at CERN in the framework of CERN Neutrino Platform (WA104/NP01 project) before being shipped to FNAL, where ICARUS will operate beneath the SBN Far Site Building. The refurbishing consisted in: new cold vessels, purely passive insulation; renovated cryogenic/LAr purification equipment; flattening of TPC cathode (the punched stainless-steel panels, 58% transparency, underwent a thermal treatment improving planarity to few mm); upgrade of light collection system, and new higher performance TPC read-out electronics.

In section 2, we will see what is the sterile neutrino puzzle, whose study is one of the main points of the SBN program and the fundamental reason for the upgrade of ICARUS. In section 3 we will review the current performance of ICARUS, achieved during the 2010-2013 Gran Sasso run. In section 4 and 5, we will talk about the light collection system and electronics, respectively. Finally, in section 6, we will analyse the essential need for a Cosmic Ray Tagger (CRT) system.

2. Sterile neutrino puzzle

Anomalies have been collected in last years in neutrino sector despite the well-established 3-flavour mixing picture within Standard Model: appearance of $\nu_e$ from $\nu_\mu$ beams in accelerator experiments (LSND + MiniBooNE, combined evidence $> 3\sigma$) [1]; disappearance of anti-$\nu_e$, hinted by nearby nuclear reactor experiments (ratio observed/predicted event rates $R = 0.9384 \pm 0.024$) [2]; disappearance of $\nu_\mu$, hinted by solar neutrino experiments during their calibration with Mega-Curie sources (SAGE, GALLEX, $R = 0.84 \pm 0.05$). [3] These results hint to a new "sterile" flavor, described by $\Delta m^2 \sim eV^2$ and small mixing angle, driving oscillations at short distance.

ICARUS constrained $\Delta m^2_{\text{new}} \leq 1 eV^2$, and small mixing: Planck data [4] and Big Bang cosmology point to at most one further flavor with $m_{\text{new}} < 0.27 eV$; no evidence of $\nu_\mu$ disappearance in MINOS and IceCube in 0.32-20 TeV energy range; recent reactor data (especially NEOS) are intriguing but inconclusive. New results are expected from ongoing/new experiments at reactor/radioactive source.

The experimental scenario calls for a definitive clarification.

ICARUS searched for $\nu_e$-excess related to LSND-like anomaly with CNGS neutrino beam ($\sim 1\%$ intrinsic $\nu_e$ contamination) despite the larger $L/E_\nu \sim 36.5 \text{ m/MeV}$ when compared to $L/E_\nu \sim 1 \text{ m/MeV}$ for LSND and MiniBooNE; LSND-like oscillation signal would average to $\sin^2(1.27\Delta m^2 L/E) \sim 1/2$; compared to MINOS and T2K, ICARUS operated in a $L/E_\nu$ range
where contributions from standard oscillations are not yet too relevant. No excess was observed in a $7.93 \times 10^{19}$ pot sample: $7 \nu_e$ charged current (CC) events compared to $8.5 \pm 1.1$ expected in absence of effect, providing the limits:

$$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \cdot 10^{-3} (90\% \text{C.L.})$$
$$P(\nu_\mu \rightarrow \nu_e) \leq 7.60 \cdot 10^{-3} (99\% \text{C.L.})$$

ICARUS restricted the allowed LSND parameters to a narrow region $\Delta m^2 < 1eV^2, \sin^2 2\theta \sim 0.005$ where all positive / negative experimental results can be coherently accommodated at 90% C.L., see figure 1.

**Figure 1.** Parameter space experimental limits for a sterile neutrino

SBN experiment will likely clarify both LSND and reactor anomalies by precisely and independently measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance, mutually related through

$$\sin^2 (2\theta_{\mu e}) \leq \frac{1}{4} \sin^2 (2\theta_{\mu x}) \sin^2 (2\theta_{\tau x})$$

### 3. Performance
In this section we will show the performance achieved by ICARUS with CNGS beam and cosmic neutrinos.

As a tracking device, T600 allows precise 3D event topology reconstruction with $\sim 1mm^3$ resolution for any ionising particle.

The detector is also a full sampling homogeneous calorimeter: total energy is reconstructed by charge integration with excellent accuracy for contained events (see eq. 1); the momentum of non contained muons is calculated by Multiple Coulomb Scattering (MCS).
\[ \sigma(E) = \begin{cases} 
11\% / \sqrt{E}(\text{MeV}) + 2\% & \text{low energy electrons} \\
3\% / \sqrt{E}(\text{GeV}) & \text{electromagnetic showers} \\
30\% / \sqrt{E}(\text{GeV}) & \text{hadron showers} 
\end{cases} \] (1)

Muon momentum measurement by MCS is essential for escaping muons and can also used to complement the range measurement for stopping muons. RMS of muon deflection angle \( \theta_{RMS} \) depends on momentum \( p \), spatial resolution and segmentation. Such method, developed in [5] by ICARUS collaboration, has been validated comparing \( p_{MCS} \) with the corresponding calorimetric measured \( p_{CAL} \) for \( \sim 10^3 \) stopping muons (track length > 5 m, of which 4 m are used, corresponding to \~4-5 interaction lengths in LAr) from CNGS \( \nu_\mu \) interacting in upstream rock. A \( \Delta p/p \sim 15\% \) resolution on average has been determined in 0.4 - 4 GeV/c range.

LAr technology permits a remarkable e/\( \gamma/\pi^0 \) separation and a powerful particle identification by \( dE/dx \) vs range (0.02 \( X_0 \) sampling, where \( X_0 = 14 \text{ cm} \) is the interaction length in LAr). There are three ”handles” to separate e/\( \gamma/\pi^0 \): 1) \( dE/dx \) profile corresponds to a single (for electrons) vs. double (for photons) m.i.p. (minimum ionization particle), 2) photon conversion separation from primary vertex (lower for pions), 3) invariant mass of \( \pi^0 \). The unique detection properties of the LAr-TPC allow to identify unambiguously individual e-events with high efficiency combining the informations of Collection and Induction2 views.

4. Light collection system

Currently, in ICARUS, light has simply been integrated over all the PMT’s. Fine, but light collection can do more than just the generation of a trigger signal. It can also be used to identify the time of occurrence \( t_0 \) of each interaction with high time precision, and to recognise the event topology for fast selection purposes.

To fulfil its goal a light collection system needs high detection coverage (to be sensitive to energy deposition in LAr down in energy to 100 MeV), high detection granularity (for space resolution purposes), fast time response (\~1 ns) to allow accurate time tracking of each event in the T600 drift window and to take advantage of the available 2 ns/19 ns bunched beam structure of the Fermilab Booster facility. Different geometries and cathode coverage area (fraction of the wire plane surface covered by PMT windows) have been tested. The 90 Hamamatsu R5912-MOD series (8”, 10 dynodes) PMT’s per TPC layout (with 5% cathode coverage area) configuration shown in figure 2, has been chosen. Grey blocks represent PMT’s positions. Longitudinal resolution is better than 0.5 m (effective Q.E. = 5%). A total of 4 modules (so 400 PMT’s including 10% of spares) will be used for ICARUS-T600.

Hamamatsu R5912-MOD series are rated for cryogenic temperature, as they feature a cathode with platinum under-layer. PMT sand blasted glass windows is coated by \~200\mu g/cm^2 of Tetra-Phenyl-Butadiene (TPB) wavelength shifter to detect the \( \lambda = 128 \text{ nm} \) scintillation light in LAr. Each PMT is enclosed in a wire screening cage to prevent induction of PMT pulses on the facing TPC wires. PMT timing/calibration will be provided by a LASER light system.

Figure 2. Chosen layout per TPC of the PMT’s, represented by grey boxes. This layout includes 90 PMT’s.
We tested all the PMT’s before installation in the T600, to verify their compliance with the required functioning specifications. PMT’s tests were organised in different CERN areas: tests at warm temperature were carried out in consecutive bunches of 16 samples in a dark room and a dedicated laboratory, whereas cryogenic tests were accomplished using a cryogenic facility which allowed the simultaneous measurement of 10 PMT’s in LAr bath, as the producer made only a mechanical check in liquid nitrogen. Measurements included the gain as a function of the power supply, the peak-to-valley ratio, the dark count rate, the linearity of the response as a function of the light intensity and uniformity of the cathode surface. As expected the PMT’s show in general an almost constant relative variation of the gain, peak to valley ratio and dark counts from room temperature down to 87K.

The achievement of the required ∼1 ns timing resolution requires a PMT timing calibration system to compensate individual channel delays and transit-time drifts.

5. ICARUS Electronics

The general approach to the trigger system is the centralisation of the basic functionalities into the NI-PXI crate already used during previous ICARUS run at LNGS, with the following requirements:

- at least one FPGA will be devoted to time critical processes, as clock generation, handling of beam gates and time-stamping of signals;
- one FPGA will be dedicated to manage the PMT signals;
- one Real Time controller will handle handshake with DAQ;
- one FPGA will be dedicated to manage the signals coming from other equipment of the far detector.

Architecture of ICARUS electronics at LNGS was based on analogue low noise "warm" front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression, trigger information. The signal to noise ratio $S/N \sim 9$ in Collection and $\sim 0.7$ mm single hit resolution, result in a precise spatial event reconstruction and muon momentum measurement by MCS. The improvements on electronics concern:

- serial 12 bits ADC, one per ch, 400 ns sampling synchronous on the whole detector, whereas previous boards were aligned within 400 ns;
- serial bus architecture with Gbit/s optical links to increase the bandwidth (10 MHz);
- new compact design to host both analogue/digital electronics (single high performance FPGA) directly on ad-hoc signal feedthrough flanges acting as electronics backplane;
- analogue front-end for a better event reconstruction
  * a faster shaping time $\sim 1.5 \mu s$ of analogue signals to match electron transit time in wire plane spacing;
  * a drastic reduction of undershoot in the preamp response as well as of the low frequency noise while maintaining a same or better $S/N$;
  * a same preamp for both Induction and Collection wires.

In addition the full 400 ns synchronous signal sampling on the whole detector will allow to slightly improve the resolution on muon momentum by MCS.

6. Cosmic ray tagger

ICARUS at FNAL will face a more challenging experimental condition than at LNGS, requiring the identification of neutrino interactions amongst 11 kHz of cosmic rays. A 3 m concrete overburden will remove contribution from charged hadrons/γ’s. Moreover $\sim 11$ muon tracks will occur per triggering event in 1 ms TPC drift readout; the associated photons represent a
serious background source for $\nu_e$ search since electrons produced via Compton scattering / pair production can mimic a genuine $\nu_e$ CC event.

Rejecting cosmic background, i.e. reconstructing the triggering event, would require to precisely know timing of each track in the TPC image, exploiting a much improved light detection system (described in section 4), high granularity and $\sim$ ns time resolution, and an external cosmic ray tagger to detect incoming particles and their direction of propagation by time-of-flight measurements. The latter may be done via scintillating bars surrounding T600 (aim: 98% coverage) equipped with optical fibers to convey light to SiPM arrays.

Top coverage of the CRT is under INFN/ CERN responsibility. FNAL is recovering modules by MINOS/Double Chooz for side and bottom.

7. Conclusions
LAr-TPC detection technique has been taken to full maturity with ICARUS-T600, a result of many years of R&D with continuous support of INFN. ICARUS completed in 2013 a successful continuous 3-year run at LNGS exposed to CNGS neutrinos and cosmic rays, obtaining remarkable physics and technical achievements, proving the effectiveness of the single phase LAr-TPC technology for neutrino physics. The ability in reconstructing neutrino interactions with complex topologies in a broad energy range, combined with an efficient identification of primary electrons and a unique $e/\gamma/\pi^0$ separation, allows rejecting backgrounds in the search for $\nu_\mu \rightarrow \nu_e$ transitions at an unprecedented level. ICARUS performed a sensitive search for a potential $\nu_e$ excess related to the LSND-like anomaly with CNGS beam defining a narrow region at $(\Delta m^2, \sin^2 2\theta) \sim (1 eV^2, 0.005)$ which has to be investigated to definitively settle the LSND hint of a sterile neutrino. ICARUS underwent a major overhauling at CERN and has been transported to FNAL to be exposed to Booster and NuMi neutrinos. The SBN experiment will provide a clarification of the sterile neutrino issue, both in appearance and disappearance modes.

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