The WA104 Experiment at CERN

Maurizio Bonesini  
(on behalf of the ICARUS/WA104 Collaboration)

Sezione INFN Milano Bicocca,  
Dipartimento di Fisica G. Occhialini,  
Piazza Scienza 3, 2016 Milano  
Italy  
E-mail: maurizio.bonesini@mib.infn.it

Abstract. The refurbishment operations, inside the WA104 programme at CERN, of the Icarus T600 detector, in view of its possible run on the FNAL short-baseline Booster neutrino beam (BNB), will be outlined.

1. Introduction
In recent years, in disagreement with the established picture of three neutrinos [1], several experimental “anomalies” both at reactors and accelerators have been reported [2]. They hint to new physics with the possible existence of one or more “sterile” neutrinos with masses at or below the few eV range. An important contribution to the sterile neutrino search has been recently obtained by the ICARUS Collaboration at LNGS on the CNGS beam, as also reported at this conference [3].

New searches for sterile neutrinos have been proposed a reactors, looking for oscillations with \( L/E \sim 1 \text{ m}/\text{MeV} \) [4] or using intense radioactive sources [5]. In addition, the muSTORM project, based on a low energy neutrino factory, for a precision search of sterile neutrinos has been proposed [6]. With regards to the present scenario, the best opportunity will be provided however by a dedicated accelerator-based neutrino experiment, where the presence of the oscillation signal in \( \nu_e \) appearance and disappearance modes as well the \( \nu_\mu \) disappearance can be investigated with the same experimental setup.

A new experiment with a set of three liquid Argon (LAr) TPC detectors (LAr1-ND, MicroBooNE and ICARUS T600), at different baselines along the Booster Neutrino Beam (BNB) at FNAL, has been recently proposed [7] and will soon allow a very sensitive search for \( \Delta m^2 \sim 1 \text{ eV}^2 \) neutrino oscillations in different channels. The ICARUS T600 detector will operate as far detector at 600 m and the WA104 programme at CERN has therefore been conceived for the needed refurbishment operations.

While, in the deep underground conditions of the LNGS laboratory, a single prompt trigger has always ensured the unique timing connection of the main image of the event for the T600 detector, at FNAL, at shallow depths, several additional cosmic muons (\( \sim 10 \)) will be present in the 1 ms drift time, giving problems for track reconstruction. A 4\( \pi \), segmented cosmic muon tagging system (CTS) to identify cosmic rays entering the detector, will have to be designed and constructed. Available technologies to realize this system (area \( \sim 1000 \text{ m}^2 \)) include either resistive plane chambers (RPC) or scintillator slabs read out by photomultipliers or SiPM.
In addition, the system for the detection of the light emitted in LAr (at \( \sim \) 128 nm) by ionizing particles will have to be upgraded, to allow both a more precise event timing and localization and the exploitation of the bunched beam structure of the BNB beam at FNAL (1.15 ns every 19 ns) to reject out-of-bunch cosmics, as proposed in [8].

2. The ICARUS T600 detector

The present ICARUS T600 cryogenic detector is made of two identical modules, \( 3.6 \times 3.9 \times 19.6 \text{m}^3 \), for a total mass of \( \sim 760 \) tons of Liquid Argon (\( \sim 476 \) active mass). Each module is equipped with 2 chambers on the long sides, with three readout planes with wires at \( 0^\circ, \pm 60^\circ \). With a 3 mm pitch and a 3 mm plane spacing, there are about 54000 readout wires. The two TPCs of each module share a common cathode, placed in the middle. Electrons have a maximum drift length of 1.5 m, in a uniform electric field of 500 V/cm. A schematic layout of the detector is shown in Figure 1 (for more details see also [9]).

![Figure 1. Schematic layout of the present T600 detector.](image)

The LAr TPCs are presently complemented by a system of 54+28 8” PMTs, coated with a TPB wavelength shifter, to detect the scintillation light emitted at \( \sim 128 \) nm by crossing ionizing particles [10].

The T600 detector has been exposed to the CNGS neutrino beam in 2010-2012, with a total statistics of \( 8.6 \times 10^{19} \) p.o.t and a detector livetime in excess of 93%.

A key feature of the T600, in view of new larger mass LAr TPCs, is the achievement of very long electron mobility [11]. To ensure long drift path for ionisation electrons without appreciable attenuation, the level of electronegative impurities in LAr must be kept exceptionally low (order some ppt). A lifetime in excess of 16 ms (\(< 20 \) ppt \( O_2 \) equivalent) was obtained since April 2013, thus demonstrating the effectiveness of single-phase LAr-TPC technique for huge detectors (up to 5m drift).

During its operation, the T600 detector demonstrated excellent detection properties, such as:

- good 3D reconstruction capabilities (\( \sim 1 \text{ mm}^3 \) spatial resolution), with accurate ionization measurement;
- good calorimetric energy reconstruction \( \left( \sigma(E)/E \simeq 0.03(0.30)/\sqrt{E}(\text{GeV}) \right) \) for e.m. (hadronic) showers;
- good particle identification via dE/dx measurement;
- momentum reconstruction of non contained \( \mu \) via Multiple Scattering (\( \Delta p/p \simeq 16\% \) in the 0.4-4 GeV/c range of interest for the future short and long baseline \( \nu \) experiments).
3. Foreseen upgrades of the T600 detector: the WA104 programme

The T600 detector has been transported to CERN at the end of 2014 for overhauling and refurbishment, in view of its future use on the FNAL BNB beam as far detector [7] or on the new LBNF long-baseline beam, as a possible near detector. One module, inside the clean room at CERN Bldg 185, is shown in figure 2.

![Figure 2. One module of the T600 detector inside the clean room at CERN Bldg. 185.](image)

The WA104 programme at CERN foresees the following main operations on the T600 detector:

- use of new cold vessels and new purely passive thermal insulation, refurbishing in parallel the cryogenic and purification equipment;
- implement a new cathode with better planarity;
- upgrade of the light collection system with new PMTs;
- upgrade of the existing “warm” electronics.

Further R&D activities will be carried on in parallel (including some specifically related to the future LBNF programme at FNAL) and will encompass:

- design of a cosmic tagging system for operations at shallow depths of the LAr TPCs;
- study of magnetization for the LAr TPCs;
- consequent replacement of the PMTs with photodetectors (such as the SiPM) insensitive to external magnetic fields;
- LAr doping.

3.1. New thermal insulation and vessels

A purely passive insulation has been chosen for the refurbishing of the T600 at CERN, coupled to a standard cooling shield with boiling $\text{N}_2$. The technique has been developed since 50 years and is widely used for large storage vessels and ships for liquefied natural gas [12]. Polyurethane foam has been chosen as insulation, with a thickness of 600 mm for the bottom and lateral sides and 400 mm for the top side. With this configuration, the heat loss through the insulation will
be $\sim 6.6$ kW, giving a total heat load of $\sim 12$ kW, including all external heat contributions (cables, pumps, ...). The adopted layout is shown in Figure 3.

Taking into account the expected heat loss, about 100K (273K) liters of LN2 (LAr) will be needed in the cooling phase of the detector for each module of the T600. The original scheme of the ICARUS T600 cryogenics and LAr purification systems will be preserved, re-using most of the present plant.

3.2. Upgraded light collection system

Operations of the T600 detector at shallow depths will require an improved light collection system, able to work with energy depositions down to $\sim 100$ MeV. The new light collection system will have to localize the track associated with the light pulse with an accuracy better than 1 m along the longitudinal $z$ coordinate, to allow efficient cosmic muons rejection. With the PMTs’ layout shown in figure 4, a reconstruction in the $z$ coordinate with a FWHM of 19, 24 or 38 cm will be obtained with 27, 54 or 90 PMTs per module side. To exploit the BNB bunch structure, for further rejection of out-of-bunch cosmic events, an overall time resolution $\sim 1$ ns will be needed. This will require an accurate time calibration of the PMTs system.

Tests are under way to select the most suitable PMT model [13]. Three large area ($8^\circ$) PMTs: Hamamatsu R5912 Mod and R5912-02 Mod and ETL 9357 KFLB are under study, both at room and cryogenic temperature. Their main characteristics are shown in Table 1.

|                   | Hama R5912 | Hama R5912-02 | ETL 9357 KFLB |
|-------------------|------------|---------------|--------------|
| no. dynodes       | 10         | 14            | 12           |
| Gain (typ)        | $10^7$     | $10^9$        | $10^7$       |
|                   | (at 1500 V)| (at 1700 V)   | (at 1500 V)  |
| risetime (ns)     | 3.8        | 4             | 3.5          |
| TTS (FWHM ns)     | 2.4        | 2.8           | 4            |
| dark current (nA) | 50         | $10^3$        | 10           |
| Q.E. at 390 nm (%)| 25         | 25            | 18           |

These PMTs have borosilicate glass windows and bialkali photocathode with platinum undercoating, to restore photocathode conductivity at low temperatures. Sensitivity in the
Figure 4. Left panel: foreseen PMTs layout for one side of one module. Right panel: rendering of the installation of PMTs inside one module.

VUV range is obtained via a coating of the sanded photocathode window with a WLS (TPB in this case). The quantum efficiency (Q.E.) in the VUV region was measured with a McPherson 234/302 VUV monochromator, equipped with a McPherson 632 Deuterium lamp. The right panel of figure 5 shows the Q.E. measured for these PMTs. For cryogenic tests, PMTs are directly immersed in a LN2 bath (T=77 K) and measurements are taken after few days of rest. Gain both at room and cryogenic temperatures are shown in the left panel of figure 5. All PMTs show good photocathode uniformity and a linear behaviour.

Figure 5. Left panel: gain as a function of HV, for the different types of tested PMTs. Right panel: Q.E. for the different types of tested PMTs, coated with TPB.

For gain, linearity and photocathode uniformity measurements, PMTs were illuminated with a 405 nm NICHIA NDV1413 laser diode, using an Avtech AVO-9A-C-P2-LARB pulse generator
Figure 6. Linearity for the Hamamatsu R5912 PMT under test, at room and cryogenic temperatures.

and a connecting 7\,\mu m core, 3m long optical fiber. The linearity of one Hamamatsu R5912 PMT, both at room and cryogenic temperatures, is shown in figure 6.

3.3. New electronics
The architecture of the T600 wires electronics was based on a custom design analogue low noise amplifier, a multiplexed 2.5 MHz 10-bit ADC and the VME backplane for data transfer. A S/N ratio better than 10 and a single point spatial resolution around 0.7 mm were thus obtained. The new design of the electronics chain foresees:

- a modern serial switched I/O for data flow, giving transfer rates up to a few Gb/s (see Figure 7 for details), as compared to the 8-10 Mb/s of the VME standard;
- one serial (10-12 bits) ADC per channel, allowing synchronous sampling within the 400 ns sampling window;
- a more compact design for both analogue and digital electronics (512 channels) integrated in the ad-hoc flange design (see Figure 8);
- the digital part is contained in a single FPGA per board, that handles the signal filtering and organizes the infos provided by the ADCs.

A cold front-end option is also under study and prototypes, developed in collaboration with BNL, will be tested at CERN.
4. Conclusions

The T600 refurbishment plans, inside the WA104 experiment, have been outlined and the detector is expected to be ready in time for the start of operations at FNAL BNB neutrino beam, in the near future. Aim of the experiment at FNAL will be a definitive clarification of the “LSND anomaly” and the collection of a significant amount of data in the energy range of interest for future long-baseline experiments.

References

[1] K. Olive et al. (PDG), Chin. Phys. C38 (20140 09001.
[2] G. Mention et al., “The Reactor Antineutrino Anomaly”, Phys. ReV. D83 (2011) 073006 ;
W. Hampel et al. (GALLEX Coll.), “Final Results of the Cr-51 neutrino source experiments in GALLEX”, Phys. Lett. B420 (1998) 114;
J. Abdurashitov et al. (SAGE Coll.), “Measurement of the response of the Russian-American Gallium experiment to neutrinos from a Cr-51 source”, Phys. ReV. C59 (1999) 2246 ;
A. Aguilar-Arevalo et al. (LSND Coll.), “Evidence for neutrino oscillations from the observation of \( \nu_e \) appearance in a \( \nu_\mu \) beam”, Phys. ReV. D64 (2001) 112007;
A. Aguilar-Arevalo et al. (MiniBooNE Coll.), “Improved Search for \( \nu_\mu \rightarrow \nu_e \) oscillations in the MiniBooNE experiment”, Phys. ReV. Lett. 110 (2013) 161801.
[3] J. Kisiel these proceedings;
M. Antonello et al., “Experimental search for the “LSND anomaly” with the ICARUS detector at the CNGS neutrino beam”, Eur. Phys. J. C73 (2013) 2599.
[4] A.S. CuCoanes et al. (Nucifer Coll), “Status of the Nucifer experiment”, J. Phys. Conf. Ser. 375 (2012) 042063.
[5] G. Bellini et al. (Borexino Coll.), “SOX: Short distance neutrino Oscillations with Borexino”, JHEP 1308 (2013) 038
[6] P.Kyberd et al., “nuSTORM: Neutrinos from Stored Muons”, arXiv:1206.0294 (2012) ;
D. Adey et al., “Light sterile neutrino sensitivity at the nuSTORM facility”, Phys. ReV. D89 (2014) 071301.
[7] M. Antonello et al., “ A proposal for a Three Detector Short-baseline \( \nu \) oscillation Program in the Fermilab Booster Neutrino Beam ”,LOI, FNAL, 2015.
[8] C. Rubbia “Using the beam bunch-structure with the T600 detector”, SNB internal report, 2014.
[9] J. Kisiel these proceedings;
S. Amerio et al., “Design, construction and tests of the Icarus T600 detector”, Nucl. Instr. and Meth. A527 (2004) 329;
C. Rubbia et al., “Underground operations of the Icarus T600 LAr-TPC, first results”, JINST 6 (2011) P07011.
[10] P. Cennini et al., “Detection of scintillation light in coincidence with ionizing tracks in a liquid argon time
projection chamber”, Nucl. Instr. and Meth. A432 (1999) 240;
P. Benetti et al., “Detection of the VUV liquid argon scintillation light by means of glass-window
photomultiplier tubes”, Nucl. Instr. and Meth. A535 (2003) 89;
A. Ankowsky et al., “Characterization of ETL 9357FLA photomultiplier tubes for cryogenic temperature
operations”, Nucl. Instr. and Meth. A556 (2006) 149.
[11] M. Antonello et al., “Experimental observation of an extremely high electron lifetime with the ICARUS-T600
LAr-TPC”, JINST 9 (2014) P12006.
[12] http://www.gtt.fr
[13] A. Falcone et al., “Comparison between large area photomultiplier tubes at cryogenic temperature for
neutrino and rare event physics experiments”, Nucl. Instr. and Meth. A (2014), in press.