PROCEEDINGS OF SCIENCE

ICARUS

Claudio Montanari*
(on behalf of the ICARUS/WA104 Collaboration)
CERN and INFN-Pavia
E-mail: claudio.montanari@cern.ch

ICARUS T600 Liquid Argon Time Projection Chamber is the first large mass (760 tons) example of a new generation of detectors able to combine the imaging capabilities of the old famous bubble chamber with the excellent energy measurement of electronic detectors. In 2013 ICARUS concluded a very successful, long duration run with the T600 detector at the LNGS underground laboratory taking data both with the CNGS neutrino beam and with cosmic rays. Several relevant physics and technical results were achieved. A joint ICARUS/SBND/MicroBooNE effort is taking place to develop a collaborative, international program at FNAL's Booster Neutrino Beam (and NuMI off-axis) with three detectors at different baselines by 2018 (near: SBND, mid: MicroBooNE, far: ICARUS). The T600 detector was transported to CERN at the end of 2014 for a series of upgrades before being taken to FNAL. The refurbishment operations, inside the WA104 programme at CERN, of the Icarus T600 detector will be outlined, with an introduction to the physics program at the FNAL short-baseline Booster neutrino beam (BNB).

XVI International Workshop on Neutrino Telescopes,
2-6 March 2015
Palazzo Franchetti, Istituto Veneto, Venice, Italy

*Speaker.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(NEUTEL2015)011

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 possibile existence of one or more "sterile" neutrinos with masses at or below the few eV range. An important contibution 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 at reactors, looking for oscillations with $L/E \sim 1m/MeV$ [4] or using intense radioactive sources [5]. In addition, the nuSTORM 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 ν_e appearance and disappearance modes as well the ν_μ disappearance can be investigated with the same experimental setup.

A new experiment with a set of three liquid Argon (LAr) TPC detectors (SBND, MicroBooNE and ICARUS T600), at different baselines along the Boster Neutrino Beam (BNB) at FNAL, has been recently proposed [7] and will soon allow a very sensitive search for $\Delta m^2 \simeq 1eV^2$ 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.

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. Instead, 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 4π, 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 m^2) include either resistive plane chambers (RPC) or scintillator slabs read out by photomultipliers or Silicon Photomultipliers (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. Physics at the FNAL Booster Neutrino Beam

The future short-baseline experimental configuration is proposed to include three Liquid Argon Time Projection Chamber detectors (LAr-TPC) located on-axis in the BNB. The near detector (LAr-ND) will be located in a new building directly downstream of the existing Short-Baselineenclosure 110 m from the BNB target. The MicroBooNEdetector, which is currently in the final stages of installation, is located in the Liquid Argon Test Facility (LArTF) at 470 m. The far detector (the improved ICARUS) will be located in a new building 600 m from the BNB target and between MiniBooNEand the NOvA near detector surface building. The detector locations were

PoS(NEUTEL2015)011

chosen to optimize sensitivity to neutrino oscillations and minimize the impact of flux systematic uncertainties as reported in [9].

Multiple LAr-TPCdetectors at different baselines along the BNB will allow a very sensitive search for high-Δm^2neutrino oscillations in multiple channels.

Figure 1 shows the full residual ν_e background predictions in each detector, including intrinsic ν_e beam events, neutral-current and ν_μCC mis-IDs, out-of-detector beam related "dirt" backgrounds, and cosmogenic photon induced electromagnetic shower backgrounds after some topological cuts. For comparison, a sample $\nu_\mu \rightarrow \nu_e$oscillation signal is also shown for each detector location corresponding to the best-fit parameters from the Kopp et al. analysis [**?**] of Δm^2= 0.43 $eV^2$and $sin^2(2\theta)$= 0.013.

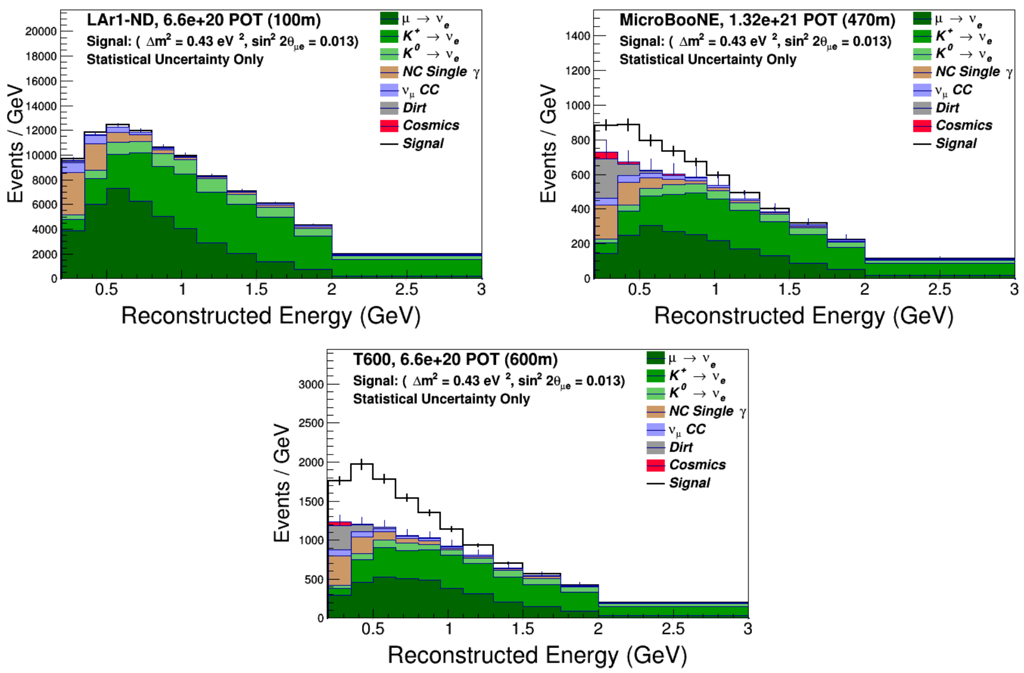

Figure 1: Electron neutrino charged-current candidate distributions in LAr-ND(top), MicroBooNE(middle), and ICARUS(bottom) shown as a function of reconstructed neutrino energy. All backgrounds are shown. A combination of the internal light collection systems and external cosmic tagger systems at each detector are assumed to conservatively identify 95% of the triggers with a cosmic muon in the beam spill time and those events are rejected. Oscillation signal events for the best-fit oscillation parameters from Kopp et al. [**?**] are indicated by the white histogram on top in each distribution.

Figure 2 presents the experimental sensitivity of the proposed Fermilab SBN program to $\nu_\mu \rightarrow \nu_e$appearance signals in the (Δm^2, $sin^2(2\theta)$) plane compared to the original LSND allowed region [11] . The LSND 99% C.L. allowed region is covered at the $\geq 5\sigma$ level above Δm^2= 0.1 $eV^2$and $> 4.5\sigma$ everywhere. Note that the region below Δm^2= 0.1 $eV^2$is already ruled out at more than 5σ by the previous results of ICARUS at Gran Sasso (see Figure **??**).

The $\nu_\mu$disappearance sensitivity for the SBN Program is also estimated. The background evaluation is not as complete as for the ν_e analysis, in particular possible contributions from dirt or cosmogenic sources are not considered, but they are expected to be small compared to the high ν_μCC

PoS(NEUTEL2015)011

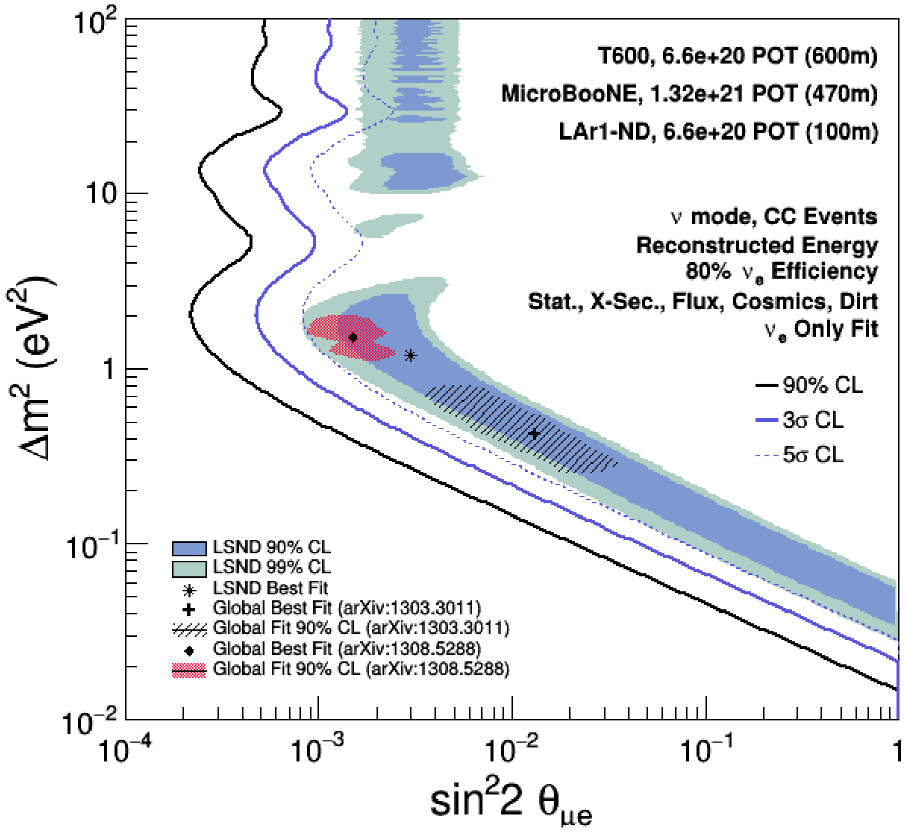

Figure 2: Sensitivity of the SBN Program to $\nu_\mu \to \nu_e$oscillation signals. All backgrounds and systematic uncertainties described in this proposal (except detector systematics) are included. The sensitivity shown corresponds to the event distributions on the right in Figure 1, which includes the topological cuts on cosmic backgrounds and an additional 95% rejection factor coming from an external cosmic tagging system and internal light collection system to reject cosmic rays arriving at the detector in time with the beam.

rate. The absolute flux and cross section uncertainties in any detector along the BNB are larger than 10%, but the high correlations between the near detector and the MicroBooNE/ICARUSevent samples along with the excellent statistical precision of the LAr-ND measurements will make the SBN program the most sensitive $\nu_\mu$disappearance experiment at $\Delta m^2 \sim 1\ eV^2$.

Figure 4 presents the $\nu_\mu$disappearance sensitivity assuming $6.6x10^{20}$ protons on target exposure in LAr-ND a nd ICARUSand $1.32x10^{20}$ protons on target in MicroBooNE. The red curve is the 90% confidence level limit set by the Short-Baselineand MiniBooNEjoint analysis [12] and is to be compared to the solid black curve (also 90% C.L.) for the LAr SBN program presented here. SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of Short-Baselineand MiniBooNE. Figure 3 shows two examples of ν_μ disappearanceoscillation signals (for $\Delta m^2 = 0.44\ eV^2$and $1.1\ eV^2$) in the three detectors for the exposures given above.

The $\nu_\mu$disappearance measurement is a critical aspect of the SBN program and is needed to confirm a signal, if seen in ν_e appearance, as oscillations. A genuine $\nu_\mu \to \nu_e$appearance can also

PoS(NEUTEL2015)011

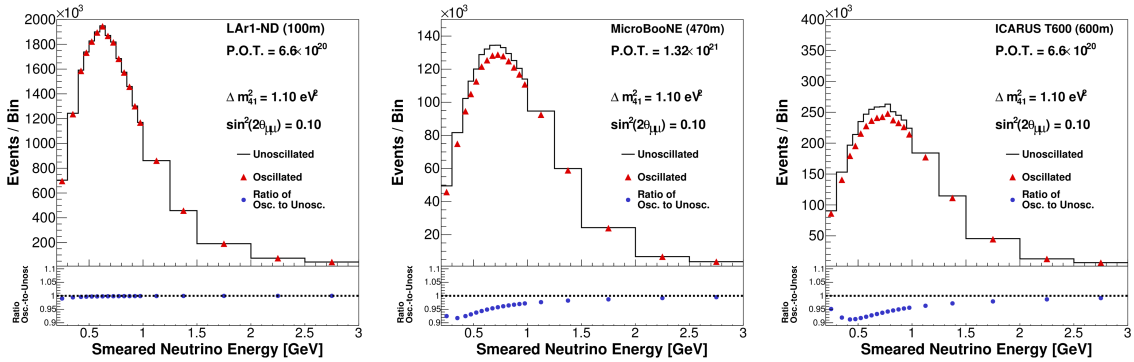

Figure 3: Examples of $\nu_\mu$disappearance signals in the SBN detectors for Δm^2= 1.1 eV^2(bottom).

be accompanied by a disappearance of the intrinsic ν_e beam component, since the three oscillation probabilities are related through a common mixing matrix. As an example, in the case of one additional sterile neutrino, $\sin^2 2\theta_{\mu e} \leq 1/4 \sin^2 2\theta_{\mu\mu} \cdot \sin^2 2\theta_{ee}$, which is valid for small mixing angles.

The ability to perform searches for oscillation signals in multiple channels is a major advantage for the FNAL SBN oscillation physics program. By collecting the $\nu_\mu$and ν_e event samples in the same experiment at the same time, correlations between the samples can be well understood and many systematics are common. This implies that a simultaneous analysis of ν_e CC and ν_μCC events will be a very powerful way to explore oscillations and untangle the effects of $\nu_\mu \to \nu_e$, ν_μ disappearance, and ν_e disappearance, if they exist, in this mass-splitting range.

3. 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 $0^0, \pm 60^0$. 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 5 (for more details see also [13]).

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 [14].

The T600 detector has been exposed to the CNGS neutrino beam in 2010-2012, with a total statistics of 8.6×10^{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 free electron lifetimes [15]. 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).

PoS(NEUTEL2015)011

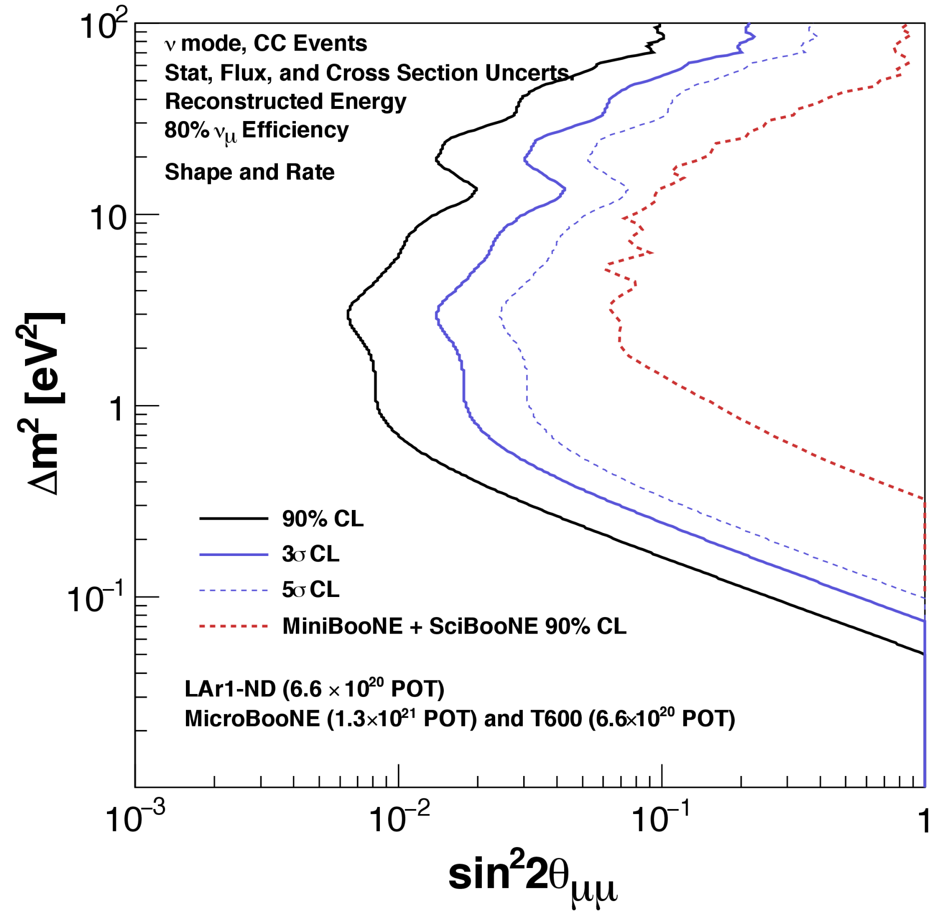

Figure 4: Sensitivity prediction for the SBN program to ν_μ disappearanceoscillations including all backgrounds and systematic uncertainties (except detector systematics). SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of Short-Baselineand MiniBooNE.

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

- good 3D reconstruction capabilities ($\sim 1\ mm^3$ spatial resolution), with accurate ionization measurement;
- good calorimetric energy reconstruction ($\sigma(E)/E \simeq 0.03(0.30)/\sqrt{E}(GeV)$ for e.m. (hadronic) showers;
- good particle identification via dE/dx measurement;
- momentum reconstruction of non contained μ 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 ν experiments).

4. 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

PoS(NEUTEL2015)011

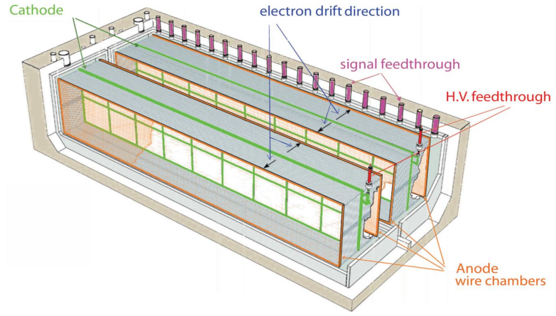

Figure 5: Schematic layout of the present T600 detector.

LBNF long-baseline beam, as a possible near detector. One module, inside the clean room at CERN Bldg 185, is shown in figure 6.

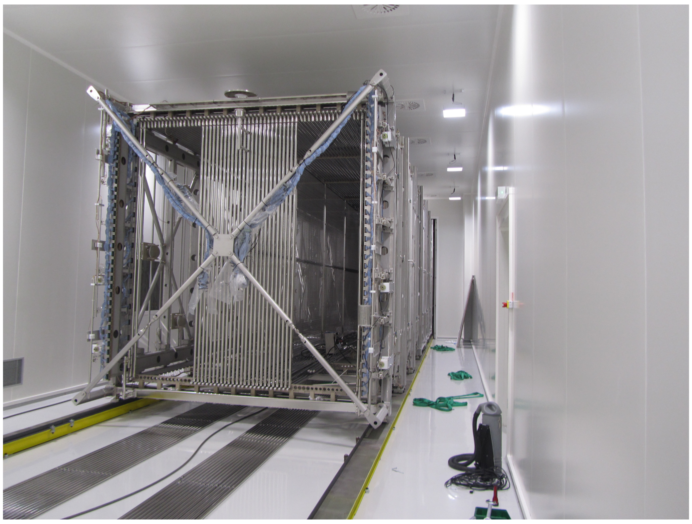

Figure 6: One module of the T600 detector inside the clean room at CERN Bldg. 185.

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 cathode with better planarity;
- upgrade of the light collection system with new PMTs;
- upgrade of the existing "warm" electronics.

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

PoS(NEUTEL2015)011

- 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.

4.1 New thermal insulation and vessels

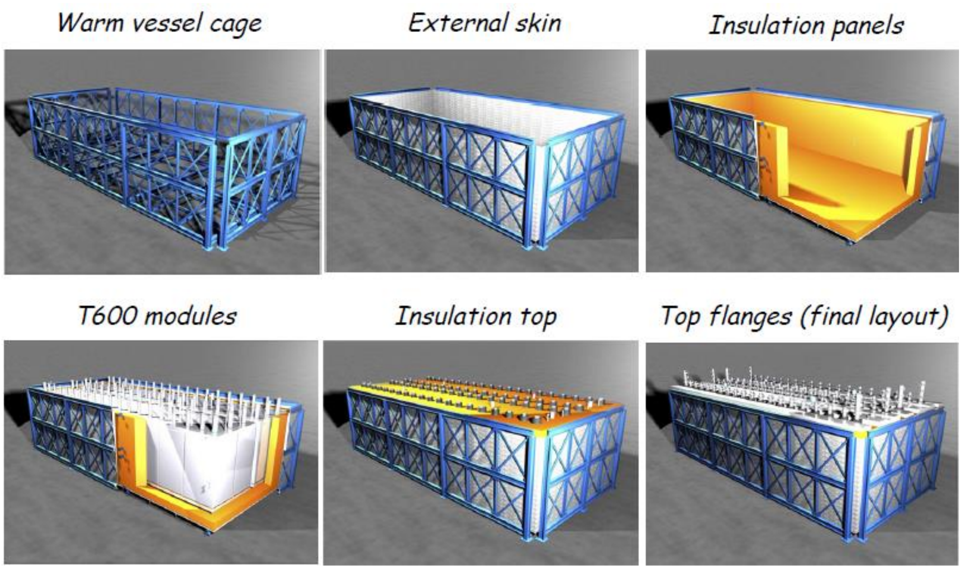

Figure 7: New T600 layout, including warm vessel and insulation panels.

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.

4.2 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 8, a reconstruction in the z coordinate with a FWHM of 19, 24 or 38 cm will be obtained with 90, 54 or 27 PMTs per module side, respectively. To exploit the BNB bunch

PoS(NEUTEL2015)011

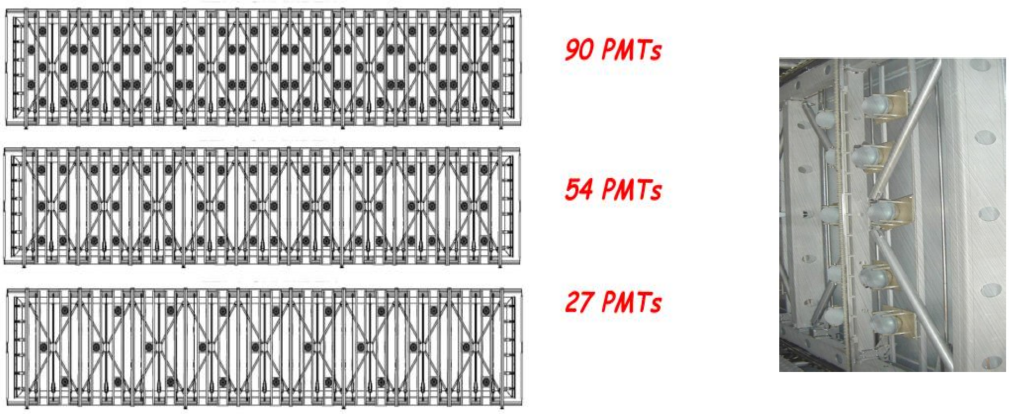

Figure 8: Left panel: foreseen PMTs layout for one side of one module. Right panel: rendering of the installation of PMTs inside one module.

structure, for futher 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.

At the time of the Workshop tests wre under way to select the most suitable PMT model [17]. Three large area (8") PMTs: Hamamatsu R5912 Mod and R5912-02 Mod and ETL 9357 KFLB have been studied, both at room and cryogenic temperature. Their main characteristics are shown in Table 1. Our final choice was Hamamatsu R5912 both because of the good performance at LAr temperature and of the extended range of linearity (about a factor 10 better than the 14 stages version, R5912-02 Mod).

Table 1: Main characteristics of used 8" PMTs.

	Hama R5912	Hama R5912-02	ETL 9357KFLB
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 under-coating, to restore photocathode conductivity at low temperatures. Sensitivity in the VUV range is obtained via a coating of the sand blasted 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 Mc Pherson 632 Deuterium lamp. The right panel of figure 9 shows the "Global Q.E." measured for these PMTs ("Global Q.E." includes the TPB conversion

PoS(NEUTEL2015)011

efficiency and related geometrical effects). 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 9. All PMTs show good photocathode uniformity and a linear behaviour.

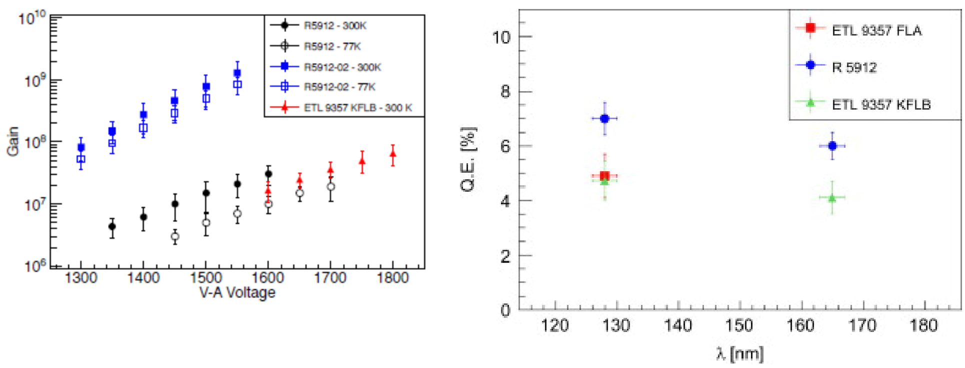

Figure 9: Left panel: gain as a function of HV, for the different types of tested PMTs. Right panel: Q.E. for the different types of tested PMTs, coated with TPB.

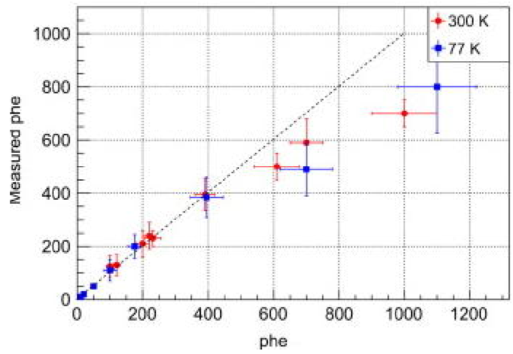

Figure 10: Linearity for the Hamamatsu R5912 PMT under test, at room and cryogenic temperatures.

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 and a connecting 7μm core, 3m long optical fiber. The linearity of one Hamamatsu R5912 PMT, both at room and cryogenic temperatures, is shown in figure 10.

4.3 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:

PoS(NEUTEL2015)011

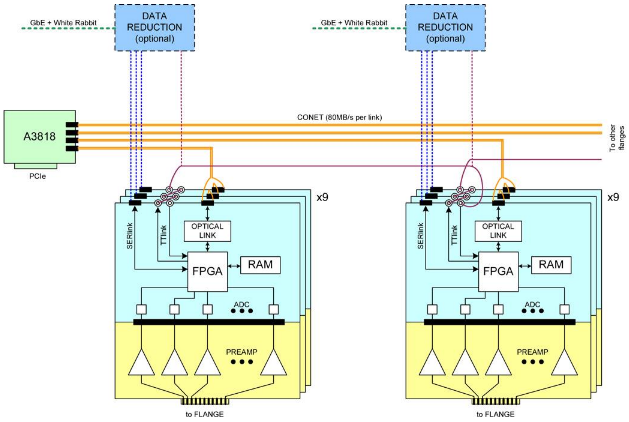

Figure 11: Schematic layout of the prototype implementing the readout system, based on a modern switched I/O on a low cost optical Gigabits serial link.

- a modern serial switched I/O for data flow, giving transfer rates up to a few Gb/s (see Figure 11 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 12);
- the digital part is contained in a single FPGA per board, that handles the signal filtering and organizes the infos provided by the ADCs.

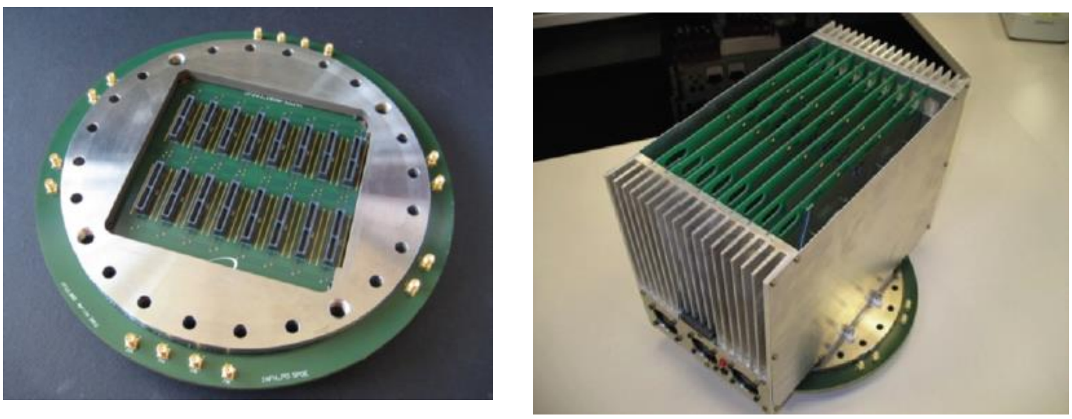

Figure 12: Left panel: prototype of the feed-through flange under test. Right panel: first prototypes of new boards under test at LNL

PoS(NEUTEL2015)011

A cold front-end option was also studied at CERN, with prototypes developed in collaboration with BNL. Due to the very short time schedule this option cannot be implemented for the next T600 installation, but it is of interest for future large mass detectors.

5. 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, within the next two years. 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 $\overline{\nu_e}$ appearance in a ν_μ beam", Phys. ReV. **D64** (2001) 112007;
A. Aguilar-Arevalo *et al.* (MiniBooNE Coll.), "Improved Search for $\overline{\nu_\mu} \mapsto \overline{\nu_e}$ oscillations in the MiniBooNE experiment", Phys. ReV. Lett. **110** (2013) 161801.

[3] 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 ν oscillation Program in the Fermilab Booster Neutrino Beam ",LOI, FNAL, 2015.

[8] C. Rubbia "Using the beam bunch-structure with the T600 detector", SBN internal report, 2014.

[9] P. Wilson et al. "Program Definition Status Report: Short-Baseline Neutrino Oscillation Program on the Fermilab Booster Neutrino Beam", submitted to the Fermilab PAC in July 2014.

[10] Joachim Kopp, Pedro A. N. Machado, Michele Maltoni, and Thomas Schwetz "Sterile Neutrino Oscillations: The Global Picture" JHEP **1305**, 050 (2013), arXiv:1303.3011 [hep-ph].

[11] A. Aguilar-Arevalo et al. (LSND Collaboration) "Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam", Phys.Rev. **D64**, 112007 (2001), arXiv:hep-ex/0104049 [hep-ex].

PoS(NEUTEL2015)011

[12] K. B. M. Mahn, Y. Nakajima, et al. (MiniBooNE and SciBooNE Collaborations) "Dual baseline search for muon neutrino disappearance at 0.5 $eV^2 < \Delta m^2 < 40$ eV^2", Phys. Rev. **D 85**, 032007 (2012).

[13] 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.

[14] 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.

[15] M. Antonello *et al.*,"Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC", JINST 9 (2014) P12006.

[16] http://www.gtt.fr

[17] 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.

PoS(NEUTEL2015)011