PROCEEDINGS OF SCIENCE

Icarus

Andrea Zani, on behalf of the ICARUS/WA104 Collaboration*
CERN
E-mail: andrea.zani@cern.ch

The ICARUS T600 detector is the largest LAr-TPC operated to date. It performed a successful three-year physics run at the underground LNGS laboratories, studying neutrino oscillations with both the CNGS neutrino beam from CERN, and cosmic rays. Among the studies carried out on the beam events, a sensitive search for anomalous ν_e appearance was performed, while a disappearance analysis is just started on the collected sample of ν_μCC. Both studies aim at verifying or excluding the experimental neutrino anomalies suggested by LSND signal and reactors and calibrations sources detectors. On the other end, cosmic rays triggers are used to study atmospheric neutrino interactions. The T600 detector is now undertaking a significant overhaul at CERN, within the CERN Neutrino Platform, that covers most detector subsystems. It will be then redeployed to FNAL, where it will act as far station for the SBN project, dedicated to solving the sterile neutrino hypothesis. This contribution will discuss LNGS analyses, as well as the overhauling activities at CERN and the preparation for the new physics run in the United States.

XVII International Workshop on Neutrino Telescopes
13-17 March 2017
Venezia, Italy

*Speaker.

PoS(NEUTEL2017)041

1. Introduction: The LAr-TPC technology development

Liquid Argon - Time Projection Chamber (LAr-TPC) technology is presented here as the first important alternative to Cherenkov radiation detection which, with its k-ton water/ice detectors, has been for years one of the key choices for studying neutrinos. Developed starting in the '80's, the LAr-TPC is an "electronic bubble chamber", allowing unambiguous identification of each ionizing track in complex ν-events, as originally proposed by C. Rubbia [CERN-EP/77-08].

The ICARUS detector in particular was born in Italy, as the results of combined effort of ICARUS Collaboration and INFN support through many years. This effort has led, through many stages of prototyping and interaction with industries, to the main result of the T600 detector, to date the largest LAr-TPC ever operated, ~500 t of sensitive mass [1, 2].

2. The T600 detector

The ICARUS T600 detector was constructed in Pavia, and deployed in the Hall B of the underground Gran Sasso Laboratory (LNGS), Italy. It operated successfully for more than 3 years (Oct 2010 - Dec. 2012), exposed to both the CERN-Neutrino-to-Gran-Sasso (CNGS) beam, and cosmic rays. The CNGS beam was an almost pure ν_μ beam peaked in the $10 \leq E_\nu \leq 30$ GeV range, with a $< 1\%$ contamination of $\nu_e/\bar{\nu}_e$. The detector collected neutrinos corresponding to a total of 8.6×10^{19} 400-GeV Protons-On-Target (POT) with a recording efficiency exceeding 93%.

The T600 is made by two identical modules, each made of two TPCs sharing a common cathode in the middle. Half module internal dimensions are: $3.6 \times 3.9 \times 19.6$ m^3, which translates into a total volume of 760 tons of ultra-pure LAr. The TPCs are characterized by a 1.5 m drift length, over which a uniform electric field $E_D = 500$ V/cm is maintained. Charged particle interaction in LAr produces both scintillation light and ionization electrons. The charges are drifted by the field towards the anode plane, made by three parallel wire planes, 3 mm apart and with a 3 mm wire pitch. A total of about 54000 wires is instrumented. The planes are oriented at $0^\circ, \pm 60^\circ$ with respect to the horizontal, and they are biased in such a way to have electrons going around the wires of the first two (*Induction*) planes, and being collected on the third, *Collection* plane. 74 8" photomultipliers (PMTs) collect the scintillation light, yielding timing information. The UV photons produced by LAr scintillation (at $\lambda = 128$ nm) are recovered by coating the PMT windows with Tetra-phenyl Butadiene, TPB, a wavelength shifter re-emitting light at around $\lambda = 430$ nm.

A precise measurement of the electron drift velocity ($v_D = 1.59$ mm/μs at $E = E_D$), combined with the timing information, provides the event position in the drift direction. The other two coordinates are obtained by combining the information of the three views from the TPC wires. It is therefore possible to obtain full 3D information of the tracks, and their reconstruction with a precision of few mm^3.

The electronic chain design yields continuous read-out, digitization (10-bit FADC) and independent waveform recording for each wire signal. Non-synchronous, 400-ns sampling is applied to waveforms. Data collection is triggered by the coincidence between detection of UV scintillation light produced by the primary track and the CERN-SPS proton extraction time for the CNGS beam.

PoS(NEUTEL2017)041

2.1 The T600 performance at LNGS

The T600 yielded a very high performance over many aspects during the LNGS run. A key technical achievement was an unprecedented level of LAr purity, obtained by means of continuous gas (2.5 m^3/h) and liquid (100 m^3/d) recirculation, as well as standard commercial Hydrosorb/ Oxysorb^{TM} filters. Concentration of electronegative impurities (O_2, N_2, H_2O) was always kept far below the value of 0.1 ppb - O_2 equivalent. This ensured electron drift over the full drift distance, and allowed obtaining maximum and average electron life-time of respectively 16 and >7 ms (max charge attenuation along the drift: 12%), as shown in Fig. 1,Left [3]. This is a fundamental step towards the construction of a new generation of multikton-sized detectors.

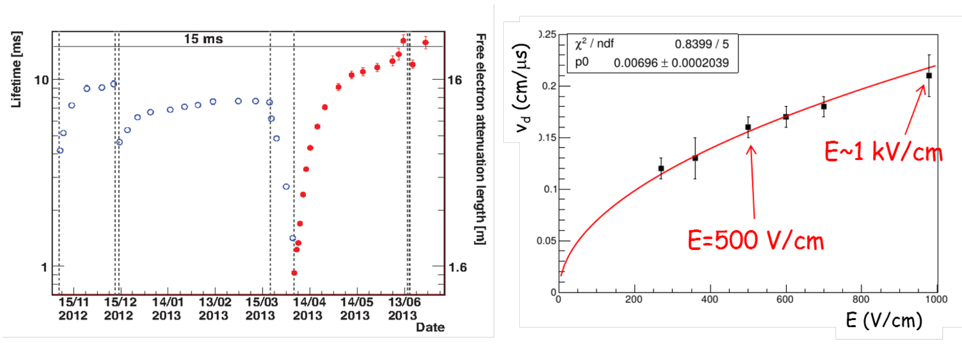

Figure 1: Technical achievements of the ICARUS T600 detector. Left: electron life-time τ_e in the T600 East half-module, as a function of time [3]. Stops of recirculation due to pump maintenance lead to the decrease in purity. The installation of a faster pump from April 2013 yields a much larger purification speed (cfr. slope of data points), and a new minimum of impurity concentration, <20 ppt O_2 equivalent. Right: measurements of electron drift velocity for different values of stable electric drift field.

From a physical point of view, the T600 is an excellent tracking device and a sampling homogeneous calorimeter: the total energy of contained events can be reconstructed with high accuracy by charge integration, with an energy resolution $\sigma_E/E = 3\%/\sqrt{E}$(GeV) for e.l.m. showers and $\sim 30\%/\sqrt{E}$(GeV) for hadronic showers.

As well, a very precise measurement of local energy depositions dE/dx was achieved: distributions of dE/dx vs *particle range* allow performing particle ID, while the observed dE/dx uniformity over the drift coordinate yields a cross check of the purity LAr evaluation. In particular, the capability to sample the dE/dx over distances of $\sim 2\%\ X_0$, together with $\sim$mm tracking, provide different handles to perform e/γ separation, distinguishing single from double *minimum ionizing particle* (m.i.p.) tracks and identifying photons conversions detached from their production vertex. This unique feature of LAr TPCs is an asset for the efficient identification of ν_eCC events while rejecting the NC backgrounds.

A more recent study [4] demonstrates the capability to achieve reliable measurement of muon momentum by use of Multiple Coulomb Scattering (MCS). The comparison between the momentum thus measured (p_{MCS}) and the one obtained via calorimetry (p_{cal}) was performed on a sample of stopping μ's produced in CNGS ν_μCC interactions in upstream rock, and stopping/decaying inside the T600 (see Fig. 2). The results show agreement between p_{MCS} and p_{cal} within 5%, when accounting for field un-uniformity due to cathode plane distortions measured at CERN (see section

4). A momentum resolution of $\Delta p/p \sim 15\%$ was achieved in the $0.4-4$ GeV/c range, which can be of interest for future short/long baseline experiments.

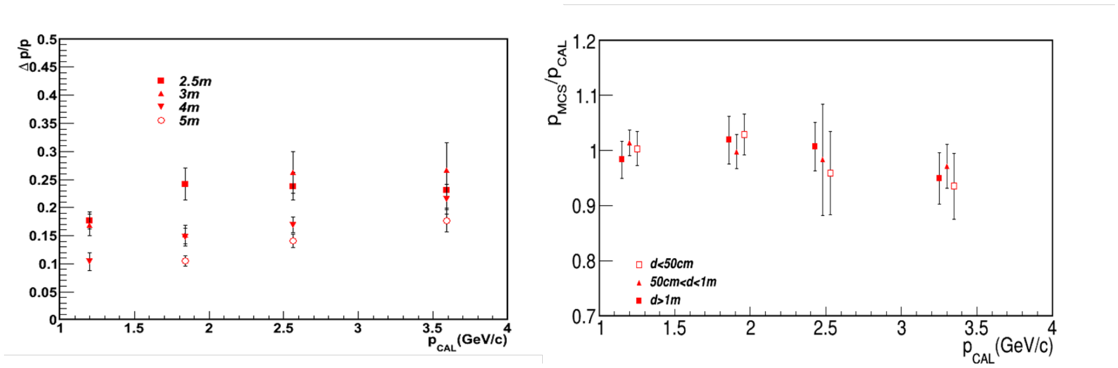

Figure 2: Left: $\Delta p/p$ in LNGS data for contained μ-tracks of different lengths; Right: p_{MCS}/p_{cal} vs p_{cal} for different distances of μ-tracks from cathode [4]. Data are corrected for the electric field un-uniformity caused by cathode distortions, described in section 4.

With the T600 0.73 kton$\times$year exposure, it is also possible to search for atmospheric ν-events. This is done with an automatic filter, used to reject incoming charged cosmics and provide neutral interaction candidates to be visually studied. The search is a significant test bench for the development of automatic algorithms, needed in high-rate, background-heavy environments, as the SBN program presented in sec. 3.2. Candidate events with energy few hundred MeV up to few GeV have been identified so far, proving the T600 reliability over a wide energy range.

Among other important physics results of the ICARUS detector, one can recall the ruling out of the superluminal neutrinos hypothesis, achieved by disproving the claim of Cherenkov-like emission by CNGS ν's [5] and measuring the ν time of flight with ns precision [6]. Another technical success, of interest for future experiments with multikton volume and several meters of drift path, was the possibility to run the T600 TPCs at different electric fields, up to $\sim$ 1 kV/cm. This allows performing ancillary measurements, as the behaviour of v_D vs E_D (see Fig. 1,Right).

3. Sterile neutrino searches

The current neutrino paradigm, established by most world experimental observations of ν-oscillation, consists of three flavors (ν_e, ν_μ, ν_τ) resulting from the mixing of three mass eigenstates (ν_1, ν_2, ν_3) with relatively small mass differences: $\Delta m^2_{31} \simeq 2.4\times10^{-3}$ eV^2 and $\Delta m^2_{21} \simeq 7.5\times10^{-5}$ eV^2 [7]. Nonetheless,we now know of several recently reported anomalies, which could hint at the presence of additional, non-weakly interacting neutrino flavours. These *sterile* states would add larger mass-squared differences participating in the mixing.

Two distinct classes of neutrino anomalies have been reported so far: first, *disappearance signals* in low energy $\bar{\nu}_e$ from nuclear reactors, beyond the expected θ_{13} effect [8], and from Mega-Curie radioactive ν_e-sources in the Gallium experiments [9, 10], originally designed to detect solar neutrinos. Secondly, experiments using muon beams from particle accelerators [11, 12] hint at evidence for a $\nu_e/\bar{\nu}_e$ *excess* in the data (the *LSND and MiniBooNE anomalies*). All these data could hint at a new sterile state, with $\Delta m^2_{new} \approx 1$ eV^2, and relatively small mixing angle $\sin^2(2\theta_{new})$.

More recent experimental results still leave open questions, as the NEOS Collaboration data on $\bar{\nu}_e$ from reactors could still be interpreted as evidence at 2.1σ of short baseline oscillation [13]; whereas the IceCube detector keeps finding no evidence of ν_μ disappearance in the 320 GeV$-$20 TeV energy range [14], and past projects in general never obtained signal evidence at $\sigma > 4$.

On the other hand data from CMB experiments [15], large scale structures and Lyman-α forest observation, bind total mass for 3 massless + 1 massive sterile ν's to $m < 0.26$ eV at 95% CL, and should effectively exclude sterile neutrino as explanation of LSND anomaly

3.1 LSND-like search by the ICARUS experiment at LNGS

The ICARUS Collaboration has exploited the excellent e/γ separation capability of the T600 to perform a search for a ν_e excess in the ν_μ CNGS beam, in order to verify the LSND hypothesis. *Seven* ν_e events were found (e.g. Fig. 3), which is compatible with expected backgrounds (from intrinsic beam contamination and standard 3ν-oscillations). The Collaboration then set limits on the oscillation probability (see Fig. 4) [16]:

$$P(\nu_\mu \to \nu_e) \leq 3.85 \times 10^{-3} \text{ (90\% C.L.)} \quad P(\nu_\mu \to \nu_e) \leq 7.60 \times 10^{-3} \text{ (99\% C.L.)} \tag{3.1}$$

The result agrees with similar OPERA measurements [17], therefore the CNGS experiments could constrain the allowed parameters to a narrow region around $\Delta m^2_{new} \sim 0.5$ eV^2, $\sin^2(2\theta_{new}) \sim 0.005$, where all the contemporary results can be coherently accommodated at 90% C.L. .

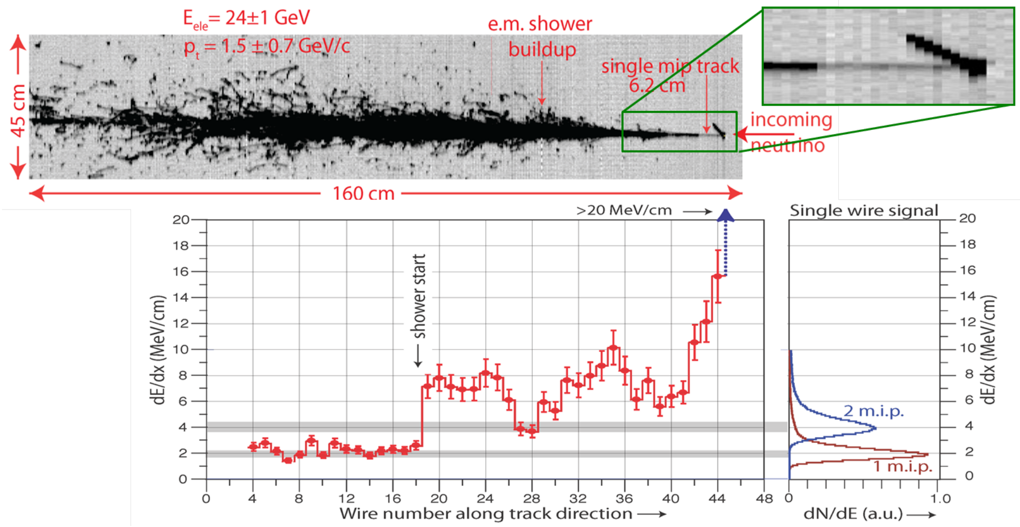

Figure 3: Example of ν_eCC event in CNGS data, with reconstructed energy of 24.1 GeV. TPC imaging clearly shows that the shower is connected to the vertex, while dE/dx analysis describes the evolution from m.i.p. behaviour to shower.

However, there is still no clear result on the sterile neutrino hypothesis, and the CNGS beam was not the perfect instrument to check the anomalies, as it had $L/E_\nu \sim 36.5$ m/MeV, far from $L/E_\nu \sim 1$ m/MeV of ν_μ beams used for LSND and MiniBooNE. Therefore the Collaboration set out to a new program, with the right configuration (short baseline, low energy beam) needed to exploit the ICARUS capabilities in order to solve the sterile-ν puzzle.

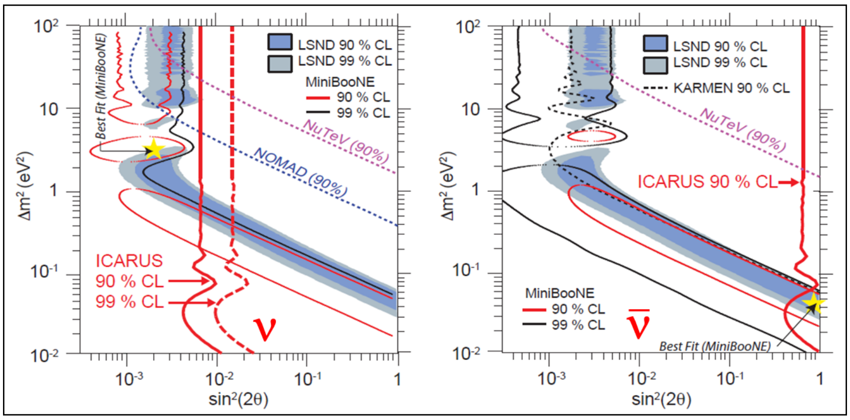

Figure 4: Limits on the non-standard oscillation probability set by the ICARUS T600 collaboration [16]. Left: neutrino case; Right: anti-neutrino case. Opera results are compatible with ICARUS ones [17].

3.2 The future: SBN and solving the sterile neutrino puzzle

A conclusive experiment, capable of clarifying the ν-anomalies at 5σ level, is based on two innovative concepts: (i) the use of LAr-TPC technology, which proved to have excellent tracking and reconstruction capabilities; (ii) multiple stations measuring the neutrino spectrum at different distances from the target. This helps eliminating systematics, as the oscillations would raise from differences in the measured spectra. Identical spectra instead would imply no oscillatory behaviour.

Such a program is in preparation at the Fermi National Accelerator Laboratory, under the name of *Short Baseline Program* - SBN [18]. The project will deploy three detectors at different distances from the target of the *Booster Neutrino Beam* - BNB at FNAL, producing ν_μ's with an energy spectrum peaked at around 700 MeV, and $\nu_e/\bar{\nu}_e$ contamination around 1%. The three LAr-TPC detectors deployed will be: (i) SBND, the near station at 110 m from target, being developed now; (ii) MicroBooNE, originally built to test the MiniBooNE results and taking data right now, at 470 m from target; and (iii) the T600, now preparing for installation and commissioning, acting as far station at 600 m from target, therefore with $L/E_\nu \lesssim 1$.

The SBN program, fully described in another contribution at this conference, will allow accumulating $6.6 \cdot 10^{20}$ protons on target in 3 years, and will permit to study both disappearance and appearance channels. According to present simulations [18], with the three detectors operating together, the LSND 99% C.L. allowed region could be covered within three years at 5σ level, in ν_e appearance mode. On the other hand the program could extend the sensitivity on ν_μ disappearance by a factor ten, with respect to accelerator-based experiments (see Fig. 5).

The T600, acting as far detector plays a key role in this project. The ICARUS Collaboration decided to perform a significant overhaul, before moving it to the US, to exploit the technology advancements of the last 20 years and prepare it for a new challenge, i.e. shallow depth operation. This implies intense cosmic-ray activity and therefore the development of new solutions (discussed below) to reject such backgrounds.

4. Overhauling the T600 at CERN

Starting in December 2014, the T600 underwent a significant overhaul at CERN, that was

PoS(NEUTEL2017)041

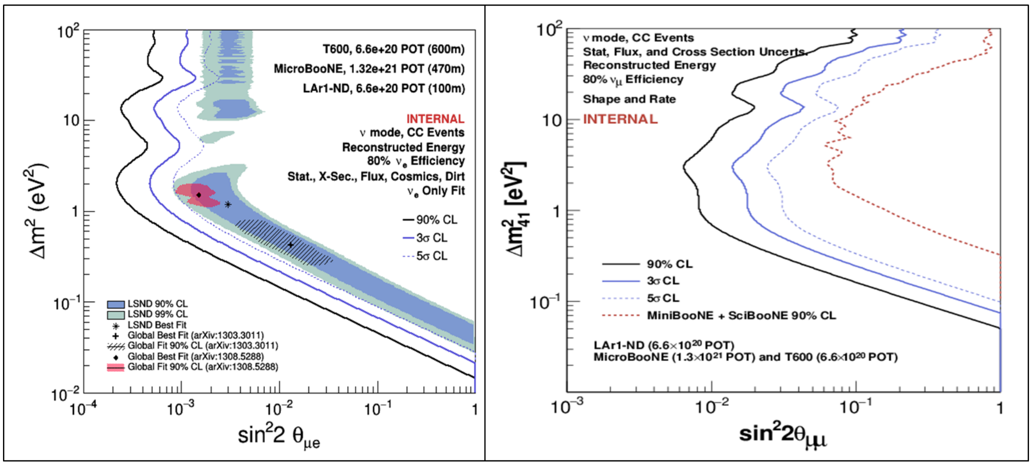

Figure 5: Left: sensitivity in the ν_e-appearance channel for three-year combined data taking (plus three more years for MicroBooNE); Right: same conditions, sensitivity achievable in the ν_μ disappearance channel. Note: LAr1-ND is the old name of SBND.

meant to introduce technology developments, while maintaining the already achieved performance. The full activity was completed in 2.5 years. The construction of the new detector containers proceeded in parallel. The same is true for a large set of tests of the new readout electronics, carried out in a separate facility.

The first module was completed and inserted in its cold vessel in December 2016. The second module, profiting of the work and experience done during the preparation of the first one, took only four months to be upgraded and made ready for shipment. The two modules were sent to FNAL in early June 2017, and reached the lab in late July, where they wait to be inserted in their building.

One of the main activities at CERN was the construction of new vessels for the detector, made of double-walled, extruded aluminum panels, welded together. The vessels underwent final assembly at CERN; a team of CERN and INFN personnel verified the leak tightness of the objects (down to $< 10^{-7}$ mbar l/s) and performed structural tests on them, by vacuum pumping the inner volumes. The results of the tests were in agreement with the calculations, and the maximal deformation of the walls, when under vacuum, was measured to be 11 mm.

A new passive insulation, made of polyurethane foam and plywood panels, was chosen to surround the new vessels. The expected heat loss through it is of 6.6 kW, i.e. around 10-15 W/m^2. The same material, coupled to a metallic membrane, was generally chosen by the CERN Neutrino Platform for its membrane cryostats, to be used in the DUNE/ProtoDUNE and SBND experiments. The membrane technology applies since almost 50 years to ship transporting liquefied natural gas, LNG; it was introduced to Neutrino Physics in collaboration with the specialized company GTT [19]. The T600 insulation and the external overall structure that supports it and contains the detectors (i.e. the *warm vessel*) were produced in Europe and then shipped to FNAL for final assembly in the SBN Far Detector (SBN-FD) building.

The cryogenics and LAr-purification circuitry of the the T600 also underwent a significant overhaul at CERN, who closely collaborated with the INFN personnel to redesign the cryo-plant, while maintaining the same general structure as in LNGS. A renovated cooling shield was designed, which runs between the vessels and the insulation, and it is made by a network of pipes circulating dual phase N_2. This allows keeping a fixed low temperature outside the vessels, and it intercepts residual heat losses. New LAr-purification filters will be used, instead of the industrial solution of Hydrosorb/Oxysorb^{TM} chosen for the LNGS run. The new filters for Oxygen were developed at FNAL and make use of Copper, instead of Chromium, for O_2 adsorption. When exhausted, the filters can be removed and re-activated, for further use. Such new solution was heavily cross-tested at CERN, with 50ℓ ICARUS Chamber (*FLIC*) facility, better described in section 4.2. A sample of such filter, containing both solutions for O_2 and H_2O adsorption, was exhausted and reactivated multiple times, to study its behaviour and verify the efficiency of the re-activation procedure.

The first intervention on the detector side concerned the cathode panels. They had intrinsic deformations from constructions, of the order of 25 mm maximal deviation from flatness; this turned out to produce electric field distortions large enough to hamper precision physics measurements, like the one of muon momentum with MCS (cfr section 2.1). The panels deformations were mapped, then they were flattened at CERN by means of a thermal treatment, which reduced the deformation by a factor 10. Finally they were re-installed. The deformation data were fed to the LNGS-run physics studies, in order to add the related correction. This proved to be especially useful with muon momentum measurement data [4].

4.1 Light Collection System

The ICARUS Light Collection System is one of the main items upgraded at CERN. While the use of large area, 8” PMTs is maintained, a major improvement in the space/time reconstruction capability will be needed for the new experiemnt, in order to perform cosmic background rejection. For this reason, each TPC was equipped with 90 Hamamatsu PMTs (360 in total), that provide large Quantum Efficiency (QE) and improved photo-cathodic coverage. The array is equipped with a new shielding, to avoid inducing spurious signals to the wires, which would be distructive in the shallow-depth background-heavy environment at FNAL. As well, a fully new electronics chain has been defined, able to achieve a $\sim$ns resolution: this will allow exploiting the BNB bunched structure to help reject the mentioned heavy cosmic backgrounds.

The PMT layout per TPC was determined by a MonteCarlo simulation, aimed at maximizing the capability of spatial localization and μ-track/e-shower separation. This guarantees wire-plane photo-cathodic coverage $> 5\%$ and spatial resolution of less than 0.5 m, even assuming a very conservatively low QE $\sim 5\%$

All the PMTs underwent a thermal cycle in LN_2 at the production site. At CERN they were tested at room temperature and 10% of them was also characterized in LAr. The room temperature characterization showed that PMT parameters were in agreement with the certification of the producers. All PMT biases were set at a gain of 10^7. Cold tests were needed to check correct operation in cold and estimate the gain loss due to the low temperature. On average, a gain loss of 50% in LAr was measured, recovered by raising the bias voltage by $\sim$150 V (see Fig. 6).

After characterization, all PMTs were covered with a thin layer of wavelength shifter, TPB, which was evaporated on their windows by using a dedicated facility. The evaporation process was optimized with mock-ups, defining parameters like evaporation time and speed, and the temperature of the powder to be evaporated. In the end a layer of 200 μg/cm^2 was chosen, optimizing light-shifting efficiency while maintaining transparency to converted photons. The average final QE of PMTs after the evaporation is of around 11%.

The tubes were installed, equipped with the mentioned shielding grid and an optical fiber each. This, coupled to a laser system to be installed at FNAL, will serve for calibration before and during operations.

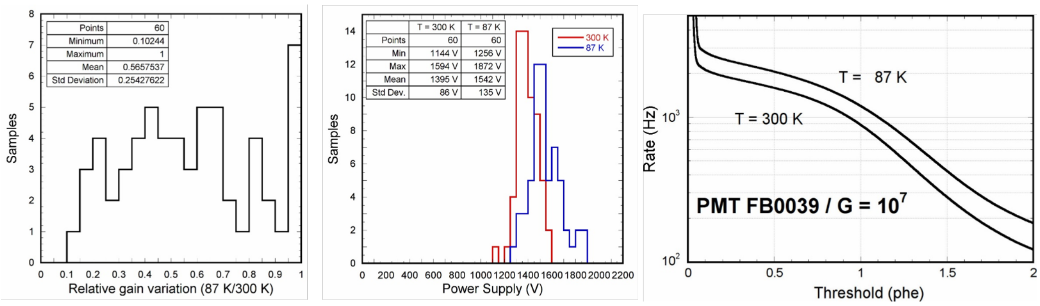

Figure 6: Overview of characterization data for the T600 PMTs. Left: relative gain variation between 87 K and 300 K operation; Centre: average bias distribution to have 10^7 gain, i.e. average voltage increase needed to restore 10^7 gain in LAr; Right: typical spectrum of dark count rate at 87 and 300 K at 10^7 gain.

4.2 Electronic Chain

The ICARUS detector will feature a new warm electronic chain, that exploits the same architecture of the previous one, but profits of newer, higher-performing components and technologies developed during the last twenty years. Each of the 96 dedicated penetrations will feature, for the TPC, a mini-crate holding 9 boards serving 64 channels each, for a total of 576 wires served by one crate. Each board hosts 64 front-end low noise charge sensitive pre-amplifiers, 64 serial 12 bit ADC (2.5 MHz), FPGA, memory, and optical link interface.

This architecture went through multiple iterations and was heavily tested first in Padova and then at CERN, where it was connected to 50ℓ ICARUS Chamber, or FLIC. This is a small, fully operating TPC, 30×30 cm^2 cross-section and ~ 50 cm drift volume, and three planes of 30 cm long wires. The three planes as biased such as to have a grid plane, an induction and a collection view. A total of 256 wires can be read out, which fills more than half of one mini-crate, installed on top of the chamber vessel.

FLIC was used to collect cosmic rays, selecting m.i.p. tracks (muons) at an angle with respect to the horizontal wire planes. Results show noise of ~2 ADC counts, i.e. $\sim 1000\,e^-$, on both planes (see Fig. 7). The unipolar Collection signal is around ~25 ADCc high, while the bipolar Induction signal structure is symmetric and almost un-distorted even in the case of showers. This allows clearly separating tracks also in Induction view, for crowded events.

The electronics hardware is in production. Boards for decoupling HV from the wires signals are also being developed and will be installed at FNAL, on the same flanges carrying the mini-crates, inside the vessels.

4.3 Cosmic Ray Tagger

As mentioned, cosmic rays will represent a significant background for SBN where, at shallow depth, they will hit in large numbers the detector: from simulations and the Pavia test experience

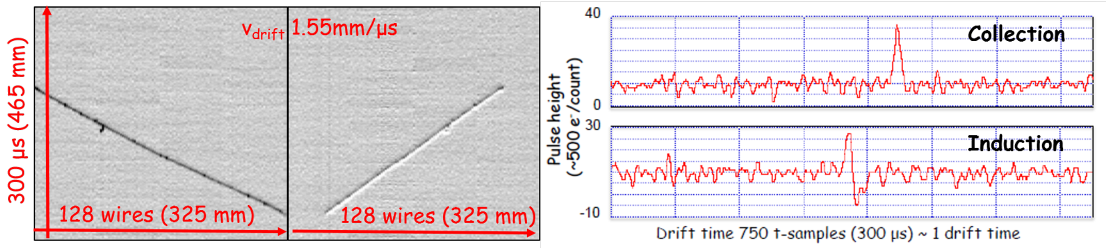

Figure 7: Cosmic muon recorded by FLIC with the new T600 warm electronic chain. Left: imaging capability of the two wire planes; Right: typical single-wire waveform for both planes. Details in text.

[1], on average12 muons are expected per drift per T300. The identification of the real triggering event, and then the reconstruction of its true 3D position, requires therefore to correctly associate timing and charge signal of each track in every TPC image. This can be achieved with two levers, namely: (i) the exploitation of the mentioned PMT ~ 1 ns time resolution; (ii) the identification of incoming cosmic particles by means of an external system, called a *Cosmic Ray Tagger*, CRT. The general design of the system foresees a layer of scintillating bars surrounding the T600, providing 98% detector coverage. The bars will be equipped with optical fibers, driving light to SiPM arrays for the readout. The bottom and sides are taken care of by FNAL, who will recover modules previously used by Double Chooz and Minos, respectively. The top part is instead under CERN/INFN responsibility, and it will feature 122 modules made of two layers of bars (around 2000 bars in total), for precise 2D localization. At CERN, scintillating bars with different characteristics and materials were tested, as well as the interconnection between the fibers and the bars. Two wavelength-shifting fibers per bar will collect the light and bring it to SiPM's with an active area of 1.3×1.3 cm^2. The production of the bars is now underway, while the design of the modules frames is almost ready. The estimated tagging efficiency of the top CRT section alone is of 80%.

5. Moving forward

The ICARUS T600 detector remains to date the largest LAr-TPC having successfully operated, for a three-year run in Gran Sasso underground laboratory, collecting both CNGS neutrinos and cosmic rays.

After the CNGS project, ICARUS was brought to CERN, to undergo a major overhauling, in the framework of the WA104 MoU between INFN and CERN. This activity, running at the time of the talk, is now completed and the T600 has taken another important and very delicate step, i.e. the trip to FNAL. This was a fundamental step in the success of the new SBN program, and it has been carefully prepared during the last year. It finally took place between June and July 2017, and now the T600 is sitting at FNAL, waiting to enter its new building, in the framework of the SBN program and the search of sterile neutrinos.

However, the T600 will also make its part for the more general future of the neutrino community and it is foreseen that it will also collect ~2 GeV off-axis neutrinos from the NUMI beam, to measure cross sections in LAr, and study the various CC/NC channels and topologies. This will deeply influence and help the production and refinement of algorithms needed for neutrino identification, which is an important asset for the upcoming DUNE experiment [20].

With the T600 at FNAL, its community is starting to move the activities in the US: INFN, CERN and FNAL are producing a strong effort to enact the installation and commissioning of detector, in order to be able to start data taking in late 2018.

References

[1] Amerio S. *et al.* (ICARUS Collab.), Nucl. Instr. and Meth. A **527**, 329-410 (2004)

[2] Rubbia C. *et al.* (ICARUS Collab.), JINST **6**, P07011 (2011)

[3] Antonello M. *et al.* (ICARUS Collab.), JINST **9**, P12006 (2014)

[4] Antonello M. *et al.* (ICARUS Collab.), JINST **12**, P04010 (2017)

[5] Antonello M. *et al.* (ICARUS Collab.), Physics Letters **B 711** 270 (2012)

[6] Antonello M. *et al.* (ICARUS Collab.), JHEP **11**, 049 (2012)

[7] Olive K.A. *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014)

[8] Mention G. *et al.*, Phys. Rev. D **83**, 073006 (2011) and reference therein

[9] Abdurashitov J.N. *et al.*, Phys. Rev. C **80**, 015807 (2009)

[10] Kaether F., Hampel W., Heusser G., Kiko J. & Kirsten T., Phys. Lett. B **685**, 47 (2010)

[11] Aguilar A. *et al.*, Phys. Rev. D **64**, 112007 (2001)

[12] Aguilar-Arevalo A. A. *et al.* (MiniBooNE Collab.), Phys. Rev. Lett. **110**, 161801 (2013)

[13] Ko Y.J. *et al.* (NEOS Collab.), Phys. Rev. Lett. **118**, 121802 (2017)

[14] Aartsen M.G. *et al.* (IceCube Collab.), Phys. Rev. Lett. **117**, 071801 (2016)

[15] Planck Collaboration, A&A, 571, A16 (2014)

[16] Antonello M. *et al.* (ICARUS Collab.), Eur. Phys. J. **C73**, 2345 (2013); EPJ **C73**, 2599 (2013)

[17] Agafonova N. *et al.* (OPERA Collab.), JHEP **1307**, 004 (2013)

[18] SBND, MicroBooNE and ICARUS Collaborations, SBN-doc-269-v5, arXiv:1503.01520v1 [physics.ins-det] (2015)

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

[20] http://www.dunescience.org/ ; Adams C. *et al.* (LBNE Collaboration), FERMILAB-PUB-14-022, arXiv:1307.7335v3 [hep-ex] (2013)

PoS(NEUTEL2017)041