Status and plans of WA104/ICARUS (WA104/ICARUS Collaboration)

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The ICARUS/WA104 Collaboration

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The ICARUS/WA104 program

The ICARUS T600 detector, the largest LAr TPC ~500 ton of sensitive mass operated so far, concluded in 2013 a very successful long duration physics experiment at the LNGS underground laboratory, taking data both with the CNGS neutrino beam and cosmic rays.

The detector already achieved relevant physics and technical results, proving the maturity of the LAr technology, demonstrating the excellent detection performance as tracking device (~1 mm³ spatial resolution) and as homogenous calorimeter. Moreover, remarkable particle identification capabilities have been determined exploiting the measurement of dE/dx vs. range. The abilities to reconstruct the neutrino interaction vertex, identify and measure e.m. showers generated by primary electrons and accurately measure invariant mass of photon pairs, allow for rejection to an unprecedented level the backgrounds in the study of νμ→νe transitions. Multiple Coulomb scattering has been demonstrated as an effective way of detecting the momentum of passing muon tracks of a reasonable length in the 0.4–4 GeV/c range.

The Argon recirculation and purification system in ICARUS has permitted to reach an extremely low electronegative impurity content in order to drift with very small attenuation free electrons created by the ionizing particles. A content less than 20 parts per trillion of Oxygen-equivalent contamination, corresponding to a free electron lifetime exceeding 16 ms, has been measured in the T600 (1). This result represents a reference for all future LAr-TPC projects involving much higher volumes where electron drift paths of several meters are required.

The smooth ICARUS operations under stable running conditions for more than three years at the nominal E=500 V/cm drift field without any failure allowed to collect ~3000 ν events (8.6 10¹⁹ pot) from the CNGS beam with remarkable detector live-time > 93 % and cosmic events (0.73 kt
year exposure). Different operating conditions have been successfully tested in the last months of run proving that ICARUS can safely stand up to ~1 kV/cm drift electric field without any discharges (see Figure 1).

ICARUS recently performed a sensitive search (2) for a potential (νe) excess related to LSND-like anomalies in the high energy νµ CNGS beam (~1% intrinsic νe contamination, L/Eν ~36.5 m/MeV). Seven electron-like events have been observed for 7.93 x 10¹⁹ pot events, consistent with the 8.5 ± 1.1 events expected from intrinsic beam (νe) component and standard neutrino oscillations, providing the limit on the oscillation probability P(νµ→νe) ≤ 3.86 x 10⁻³ at 90 % CL and P(νµ→νe) ≤ 7.76 x 10⁻³ at 99 % CL (Figure 2). Combined with all other anomalies at accelerators, nuclear reactors and with radioactive sources, this result indicates a very narrow common surviving region of the parameter space (Δm² ≈ 0.5 eV², sin²2θ ≈ 0.005 at 90% CL) which remains to be demonstrated as due to sterile neutrinos.

Presently at CERN, the ICARUS-T600 detector will be soon transported to FNAL and exposed to the 0.8 GeV FNAL Booster neutrino beam at 600 m from the target, in the framework of the SBN program (3) where measured neutrino spectra will be compared with the standard predictions simultaneously on three different locations in association with the MICROBOONE and SBND detectors. ICARUS will also collect there a large sample of νe CC events from another NUMI off-Axis beam at ~ 2 GeV, which will provide valuable information for the future DUNE project.

The ICARUS/WA104 program devoted to "Improving the ICARUS T600 Liquid Argon Time Projection Chamber (LAr TPC) in order to prepare for its operation at shallow depths" on a two-year time schedule, is almost completed. The two T600 internal detectors, completely refurbished have been installed in the new aluminum vessels and are ready for transport to Fermilab. The refurbishing included 1) the preparation of new cold vessels and new purely passive insulation, 2) the partial reconstruction of the cryogenics and purification systems, 3) the refurbishing of inner detectors with TPC cathodes with better planarity, 4) the installation of an improved scintillation light collection system 5) and a new, faster, higher-performance read-out electronics.

The new Icarus even with passive insulation will maintain the liquid nitrogen cooling system. Moreover the preparation of a ~1000 m² anti-coincidence made of scintillator planes surrounding the T600 on all sides, the Cosmic Ray Tagger (CRT) required to operate ICARUS at shallow depth, has been addressed.

As next step all activities related to the shipment and installation at FNAL of the ICARUS detector, including all necessary warm electronics and front-end infrastructure will be realized inside the framework of the new INFN/CERN common addendum (# 2) "Updated WA104 MOU-addendum for the installation and commissioning of the ICARUS T600 Liquid Argon Time Projection Chamber (LAr TPC) as far detector in the Short Baseline Neutrino (SBN) facility at FNAL."

In the framework of the SBN program at FNAL, the ICARUS Collaboration has been extended with the participation of several US teams in addition to FNAL, the so-called ICAR-US, collecting new collaborators from Arlington University, ANL, BNL, Colorado State University, LANL, Pittsburgh University and SLAC. Their main responsibilities are in particular the design and construction of the side and bottom parts of the CRT, the participation to the detector commissioning and to the subsequent physics running. A relevant software contribution is also expected for the pattern recognition and analysis of neutrino events. The integration of American
teams in a wider Collaboration will be essential for the successful achievement of the ICARUS program at FNAL.

**The new cryostats and cryogenic system.**

Purely passive insulation has been chosen for the installation at FNAL, this technique was developed for 50 years and is widely used for large industrial storage vessels and ships for liquefied natural gas. No internal membrane is required for the T600 as the detectors are placed inside two vacuum tight aluminum containers (cold vessels). The expected heat loss through the insulation is \( \approx 6.6 \) kW. A cooling shield with boiling Nitrogen is placed in the space between the thermal insulation and the cold vessels for the initial cooling of the detector and to prevent that heat coming through the insulation arrives in the LAr volume.

The reinforcing structure that will host the thermal insulation (warm vessel) was procured and built in 2016 (Figure 3). The floor and the vertical walls are now at Fermilab, ready for assembly. The top part is at CERN; it will be sent to Fermilab after the installation of the thermal insulation. GTT (a French company holding the patents of membrane cryostats) has completed the engineering design of the insulation panels.

The supports that will allow the reciprocal movements, due to thermal contraction, between the cold vessels and the thermal insulation, have been designed and procured. The warm vessel will be assembled starting from May 2017. The thermal insulation will be installed starting from July 2017.

A major activity has been the construction of the new main LAr containers (cold vessels). The new cold vessels are made by extruded aluminum profiles welded together to form a vacuum tight double walled container of parallelepiped shape (Figure 4). The two ends of the containers are bolted to allow for the insertion of the wire chambers structures. The first cold vessel was completed in October 2016. The first T600 detector was moved into the cold vessel in December 2016. The second cold vessel has been completed in February 2016 and was moved in front of the clean room hosting the second T600 detector on March 17, 2017 (see Figure 5).

Overhauling and partial reconstruction of the T600 cryogenics and purification systems is under the main responsibility of CERN. The original layout of the T600 plant has been completely revised: it is re-organized into self-consistent sub-units (skids) to be built and fully tested prior to delivery to FNAL. The construction of the new cryogenic components is in progress; delivery and start of installation at Fermilab is scheduled for September 2017.

The cold shield, that surrounds completely the two cold vessels and into which nitrogen is circulated in bi-phasic conditions to ensure temperature uniformity, is being rebuilt (Figure 6). Construction of the cold shield will take place during summer 2017.

**The new light detection system**

The realization of a new scintillation light detection system is a fundamental feature to reject the expected huge cosmic background due to the T600 operation at shallow depth. This system will provide, in addition to trigger signals, a fast spatial localization of neutrino beam associated events and a preliminary event selection based on the shape, in space and time, of the light signal. For these reasons, a sensitivity below 100 MeV of deposited energy, a \( \sim 1 \) ns time resolution, and a high granularity are required.
The new T600 light detection system consists of 360 large-surface Photo-Multiplier Tubes (PMTs) deployed behind the 4 wire chambers, hosting 90 units each (Figure 7). Hamamatsu PMT, model R5912-MOD with 8 in. diameter, were choose. They feature window made of borosilicate glass, 10 dynodes and a bialkali photo-cathode (K2CsSb) with platinum undercoating, to restore the photo-cathode conductivity at low temperature.

A complete set of 400 PMTs, including a 10% of spare units, are available. Each unit was tested before the installation in the T600, to verify its compliance with the required functioning specifications. In particular all the PMTs were tested at room temperature and 60 units were also characterized at cryogenic temperature, in a liquid argon bath. Some additional mechanical tests at cryogenic temperature were carried out in the factory for all the PMTs. Measurements were carried out in different dedicated areas at CERN, where a dark-room and a cryogenic test facility were set-up.

Since the PMT glass is not transparent to the scintillation light produced in liquid argon ($\lambda = 128$ nm), the units were made sensitive to ultraviolet photons by coating their windows with a proper fluorescent wavelength shifter re-emitting in the visible light frequencies. By means of thermal evaporation, a uniform thickness of $\sim 200$ g/cm$^2$ of Tetra-Phenyl Butadiene (TPB) was deposited on the sensitive surface of each device. For this purpose, a dedicated workshop, hosting a unique evaporation system, was set-up.

Each device was provided with a proper base circuit, supplying the high voltage for the grids, the dynodes, and the anode, and allowing the signal pick up directly from the anode. The voltage divider chain is entirely passive, and it is fabricated with SMD resistors and capacitors, all tested at cryogenic temperature. The bases were directly welded on the PMT flying leads. Since a negative power supply is adopted, two independent coaxial cables are used to provide the PMT with the high voltage and to read out the anode signal.

A dedicated, new design mechanical structure was adopted for the final installation in the TPC. This structure provides the support of each PMT in the correct position and orientation, preventing the electrical interference with the wire planes by means of additional screening grids. Moreover, each support holds up a 50 $\mu$m optical fiber in front of the PMT sensitive surface, allowing for the gain and timing equalization by means of an external laser.

The new read-out electronics, DAQ and related triggering

The motivation to implement a new electronics, with modern components, but based on the same architecture as ICARUS T600 has been described in the previous 2015 and 2016 reports to SPSC Committee. Here we summarize the progress made both in implementation/testing of the new electronics and detector wiring modifications, required by the new architecture.

The new electronics, housed onto the wire signals feed-through flange, requires wire biasing inside the detector. This avoids to have signal cables biased to the wire voltage, decoupling and biasing boards (DBB, Figure 8), made of simple R-C circuits, are installed onto the wire chamber frames. Test and installation of the DBBs are suffering a major delay due to flaws in the manufacturing and assembly processes, which involve SMD components onto the DBB. Manufacturing company and CERN are actively contributing to solve the problem by substituting R-C modules in the respective facilities. Extensive tests both at ambient temperature and in LAr are in progress on the DBB to assure the required reliability. The installation of the DBB clusters will be performed in FNAL.
A fully equipped flange with 9 TPC read out digital boards for a total of 576 channels, is in operation in CERN in the 50 liters ICARUS LAr TPC since November 2016. The boards are equipped with the new front-end amplifiers with shorter shaping time (1.5µs instead of 3µs). The 9 boards are housed in the new special designed crate installed onto the flange. The complete set-up, flange, crate, and boards, operational onto the 50 liters LAr TPC in CERN, is shown in Figure 9.

Tests with the cables of the same length as in T600 gave very positive results that are summarized in the following plots and measurements. The new sharp signal shaping proved to be effective in the reconstruction of the Induction (bipolar) signals. Different type of signals from cosmic muons are shown in Figure 10.

With faster shaping time a S/N ~9, normalized to 3 mm track length, has been measured in Collection view, to be compared with the S/N ~7 of the old electronics. Offline integration of Induction bipolar signals allows getting unipolar shapes (Figure 11) which can be exploited to achieve charge measurement also in the Induction view. This will provide a rough calorimetric measurement at ~ 30 % level of the recorded events in Induction view, improving at the same time spatial resolution. The corresponding hit-finding efficiency in Induction view is ~94% for m.i.p. muon tracks (sampling signal over~5.5 mm average track length), close to the corresponding efficiency in Collection view (> 99%) providing a full reconstruction efficiency of a m.i.p track in both Collection and Induction views. Also the S/N ratio (normalized to 3 mm track length) for Induction is now ~6 to be compared to 4 of the old electronics.

Tendering procedure has been completed and the contract for supply of 874 digital boards has been awarded. The first 10 evaluation boards will be delivered by May 2017 and after approval 100 boards per month will be delivered by the supplier. The cost of the required 874 (64-channel each) modules, for the total of 53,248 wires, is 1,750k€, which will be subdivided in few fiscal years. Tendering for 105 crate units will start soon. The flange, INFN proprietary design, were slightly modified respect to the ones used in LNGS, to house the 9 DAQ boards directly inserted in the outer connectors. They have been tested and approved. Tendering for production of 105 flanges is undergoing. The preamplifiers are in production in the facilities of the Electronics Laboratory of INFN in Padua, together with the linear power supplies.

The basic concept for trigger and data acquisition of ICARUS-T600 in the SBN Program is to use the architecture deployed at LNGS for data taking with CNGS neutrino beam. The system will consist of waveform recording of signals coming from both TPC wires and PMTs, triggered by the detection of scintillation light in coincidence with the beam extraction; the additional feature of triggering directly on the charge collected on the TPC wires will also be maintained.

A few modifications and upgrades have been introduced in order to meet the requirements of the new front-end electronics and to integrate the online and data management framework with FNAL infrastructures. Signals coming from the TPC are readout with commercial PCI boards by CAEN (A3818), capable of handling 4 optical links at >80 MB/s maximum bandwidth serving 512 channels (8 boards) each (Figure 12). As a result, 24 commercial PCs, each hosting 2 A3818, will be devoted to the readout the entire TPC channels on the ICARUS-T600 detector. Three more PCs will handle data fragments coming from PMTs and eventually the cosmic ray tagger. The final architecture foresees a total of 192 optical links dedicated to the wire readout and 24 links to the PMT boards.

A common clock, synchronized with the BNB, has to be distributed among the three sub-detectors (TPC, PMT and CRT) to guarantee the ns level relative timing needed to exploit the fine bunched beam structure (Figure 13). The common distribution at FNAL will go through a White
Rabbit infrastructure, the Ethernet network based solution developed at CERN for sub-ns synchronization of distributed systems.

Event building will rely on the common toolkit ArtDAQ, developed at FNAL. which already fulfills all the needed functionalities for the data transportation, the event fragments merging, and file system support.

A demonstrator of an artDAQ setup for one single crate has already been set up with a 50 l LAr-TPC at CERN, with cosmic rays data taking runs streaming events both in art-ROOT and Icarus legacy formats (to ease comparison and analysis software tools migration).

A simplified synchronization and trigger distribution system has been setup to allow for testing of the readout of multiple TPC front-end units, together with the PMT system. The setup will be fully equipped with boards as soon as the first batch of production will be delivered (March 2017).

The Cosmic Ray Tagger

A Cosmic Ray Tagger (CRT) will surround the T600 with scintillator planes on all sides, albeit with different implementation for the top, side and bottom areas covering ~1000 m² in total. Wherever possible, two layers will be implemented for each plane and operated in coincidences, in order to reduce the ambient radioactivity background. CERN and INFN will be responsible for the Top CRT modules, the FNAL ICARUS group will design its mechanical supports. The side and bottom parts are responsibility of the ICAR-US groups.

**Top-CRT**

According to full FLUKA simulations, the “Top” CRT on its own will intercept 80% of the Cosmic muons that produce, directly or through secondary radiation, background events in the T600 active regions (4). It will include a flat part placed immediately under the concrete shielding roof of the pit (overburden), and small inclined parts covering the corners of the roof as in Figure 14 and Ref. (5). The Top CRT will be composed of plastic scintillator bars assembled into modular square structures. A total of 125 modules, including spares, will be constructed, limiting dead spaces less than 1% of the full surface. Each module will contain two planes of 8 scintillator bars each with orthogonal orientation. Each scintillator bar will be 184 cm long, 23 cm wide and 1 to 1.5 cm thick. The light produced in the scintillator is readout by two wavelength shifting fibers, 1.0 mm diameter, polished and mirrored at one end, glued into the two grooves on the surface. The scintillator bars are placed side-by-side in the module and sandwiched between aluminum covers, each module weighing ~135 kg.

The readout will be performed with the same electronic boards used for the CRT of the near detector (SBND) which are commercialized and maintained by CAEN. This electronic board requires a coincidence between the two SiPM signals of the same bar, and provides a coincidence logic between the two layers in the module. A single board is used to read the 32 SiPM from each module.

Test measurements conducted on scintillators, fibers and SiPMs show that the light collection efficiency will be uniform within 20% over the bars, and will be high enough to allow for signal discrimination from intrinsic and ambient backgrounds. The operation of the layers in coincidences will further reduce the spurious event rate to a negligible level.
The chosen modular design of the system allows for easiness of construction, transport and installation, and for sharing of the construction among several sites.

The modules will be supported by stainless steel beams that span across the 11.2 m of lateral openings of the pit. In total 28 beams will cover the entire surface with a pitch of about 1 m. Preliminary calculations assuming IPE140 beams predict an acceptable maximum deflection, optimization is ongoing. Special supports are foreseen for the inclined parts.

Installation can start as soon as the T600 detector is completed, before the placement of the overburden plug on top of the pit. Cables and electronic boards will remain accessible from the pit.

Procurement procedures for scintillators, fibers and SiPMs are in preparation, aiming to receive all the material before the end of 2017. Production of the modules will start as soon as the first scintillator batch arrives.

**Side CRT**

Scintillator modules from the MINOS cosmic veto (6) will be reused to provide the side covering. Modules are 8 m long (plus connector), 80.5 cm wide, and 1 cm thick. They are composed by 20 bars per module (each 4 cm wide). The bars are glued to and wrapped in a light-tight aluminum skin. Light is collected by one fiber per bar, readout on both ends. MINOS modules are too long to be mounted vertically. On the long sides, and on the North side (beam exit) the panels will be mounted in two parallel layers to allow for noise reduction. Position resolution along the bar will come from time difference between readout signals on both ends. On the South side, where X-Y coverage is more important, Minos modules could be cut to 3.5 m. Readout will be provided by SiPM, use of the same CAEN board as for the Top CRT is under investigation.

**Bottom CRT**

Space and time constraints limit the possibilities for the bottom CRT. Space because of the cryostat supports, time because the bottom CRT needs to be in place before the warm vessel is constructed. MINOS modules are not enough to cover also the bottom, and their geometry is not suited for the available space. We have explored an option to install Double Chooz veto shield spare modules as a bottom CRT. Few of them are already available in the US, the rest will be shipped soon. A coverage of about 40 to 50% of the bottom area can be achieved.

**Status organization of ICARUS-T600 transport to FNAL**

The transport of the two T600 modules from CERN to FNAL has been worked on since last summer. CERN has come out with a tender on the beginning of January, and two answers were received from firms DHL and PANALPINA in the end of February.

The T600 modules will be ready for transport around mid-April. A lot of effort has been spent in describing correctly the detectors and highlighting the inherent fragilities of the components, for the firms to understand the exceptionality of the transport. On the other end, CERN personnel has gained experience moving the cold vessels within the Meyrin site, and they provided assistance in selecting tools and procedures for the modules handling. CERN is then buying all the tools needed for the handling and securing (anchoring points, slings, spreader bars), and it will certify and provide them to the winning bidder, along with detailed instructions. Said tools must be used during each handling of the modules foreseen during the transport, according to instructions.
The definition of the routes was discussed before the tender, with a consulting company providing information especially about the oversea transport. The safest course for the detector is to reach a port in northern Europe (Netherlands), then proceed in a container ship to the US coast. The travels in Europe and on the US soil can be performed by truck (extremely low deck), barge, or a combination of the two. The details on the route are to be proposed by the bidder; these include, e.g.: barge use in EU and US, starting and destination port, kind of container ship to be used. The trip is foreseen to last 4 to 6 weeks, where the time span depends mainly on the availability of container ships and the chosen route. The oversea leg alone can last 1 to 3 weeks. The choice of means of transportation on land (truck/barge) affects the total cost of the transport.

The main requirement to the bidder concerns the maximal velocities and accelerations the modules can experience. Maximal velocities are defined for the road transport. An analysis of the possible accelerations overseas was requested to the same consulting firm mentioned above, and it turns out that the highest possible values are around 1g, which is too much to bear for the detectors. In order to manage this problem, it was suggested to CERN to avoid sending the modules before May, when the Atlantic Ocean is quite calm. The bidders are then required to propose latching/securing solutions for the sea transport, which must be discussed with CERN and the Collaboration.

At the same time, CERN is taking care of defining an insurance policy for the transport. The policy will cover damages to the modules that can be recovered by intervening/substituting parts. Though it is not possible to “quote” the detectors, due to their age and the impossibility to rebuild them from scratch in a usable time-frame, a quotation of 10.5 M€ was made for the two modules. This includes: 1) estimation of cost for new parts to be bought to substitute damaged ones, based on the overhauling expenses during the last two years; 2) cost of clean room construction, and personnel work at FNAL, in case it is needed to extract again the detectors from their cold vessels, for repairs. In order to verify the good quality of the transport, and to determine responsibilities, the modules will be equipped with shock logs that will register any shock/incident/sudden acceleration suffered by the detectors. They will be read at each change of means of transport. The Collaboration reserves the right to enter and inspect the modules during the trip, should strange readings from log be recorded. The same measure was taken during the truck transport from LNGS to CERN in 2014. Presently, the received bids for the tender were opened and discussions with the firms will take place in the coming two weeks, concerning the details of the offers.

References

1) M. Antonello et al., "Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC", JINST 9, P12006 (2014).
2) M. Antonello et al., "Experimental search for LSND anomaly with the ICARUS LAr-TPC detector in the CNGS beam", Eur. Phys. J. C 73, 2345 (2013);

**Figures**

![Figure 1: The measured electron drift velocity with cosmic passing through muons as a function of the electric drift field.](image)

Figure 1: The measured electron drift velocity with cosmic passing through muons as a function of the electric drift field: $v \propto \sqrt{E_D}$. 
**Figure 2:** ICARUS experimental limits at 90 % and 99 % CL on the LSND-like $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability.

**Figure 3:** Warm vessel structure pre-assembled at the constructor premises prior to delivery to Fermilab.
Figure 4: Design of the main extruded profiles that compose the aluminum cold vessels.

Figure 5: Photo taken in front of building 185 showing, on the right, the first cold vessel with the first detector already installed inside, and second cold vessel, on the left, in front of the clean room, ready to receive the second detector.
Figure 6: Process and Instrumentation scheme of the T600 cryogenics and purification plant at Fermilab (only the first half-module is shown, for illustration purposes).

Figure 7: Final PMT installation in the T600.
Figure 8: the 32 channels DBB board.

Figure 9: the experimental set-up of the full electronics chain of the TPC read out installed onto 50 liters LAr-TPC chamber at CERN.
Figure 10: Event display of two recorded crossing cosmic muons and a corresponding signal for a selected wire in Collection and Induction view. A muon track almost parallel to the drift direction (dip angle $\theta \sim 72^\circ$) is shown.

Figure 11: Example of Induction signal integration for an event with two close cosmic muon tracks.
Figure 12: ICARUS-T600 DAQ architecture.

Figure 13: Clock and Signal distribution scheme.
Figure 14: Top CRT planes (Yellow structure), the largest scintillating plane composed of 84 modules below the concrete block, complemented with four inclined scintillating planes composed of 38 modules.