Status report of ICARUS T600

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ICARUS T600 at the INFN-LNGS Gran Sasso Laboratory is the first underground large mass Liquid Argon TPC: exposed to the CERN-CNGS neutrino beam, it has smoothly began taking data since October 2010. Its excellent resolution and 3D imaging allow an unprecedented event visualization quality combined with a good calorimetric reconstruction and the electronic event processing. In addition to the $\nu_\mu \rightarrow \nu_\tau$ oscillation and sterile neutrino search, atmospheric neutrino and matter stability will be studied.

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1. ICARUS T600 experiment

The ICARUS T600 LAr-TPC detector, presently taking data in Hall B of the INFN Gran Sasso underground National Laboratory (LNGS), is the largest liquid Argon TPC ever built. Its detection technique, based on the collection of scintillation light (5000 γ/mm at 128 nm wavelength) combined with the stereoscopic recording of the ionization signal ($\sim$ 6000 electrons per mm), was first proposed by C. Rubbia in 1977.[1]

1.1. *Detector layout and liquid Argon purity*

The ICARUS T600 detector[2] (see Fig.1) consists of a large cryostat split into two identical, adjacent and independet half-modules, with an overall mass of about 760 tons of ultra-pure liquid Argon at 89 K temperature. Each half-module, with internal dimensions $3.6 \times 3.9 \times 19.6$ m^3, houses two Time Projection Chambers (TPCs) separated by a common cathode. An electric field E$_D$ = 500 V/cm, kept uniform by field shaping electrodes, ensures the coverage of the 1.5 m maximum drift distance in 1 ms. The anode of each TPC is made of three parallel wire planes, 3 mm apart, oriented at 0° and ±60° w.r.t. the horizontal direction: in total 53248 wires are installed.

By appropriate voltage biasing, the first two planes (Induction-1, 2) are transparent to drift electrons and measure them in a non-destructive way, whereas the ionization charge is finally collected by the last one (Collection). The signals coming from each wire are continuously read and digitized at 25 MHz (1 t-sample $\sim$ 400 ns) and recorded in multi-event circular buffers operated with a 3-levels veto able to give different priorities to the trigger sources, thus minimizing DAQ dead-time. Building rate is kept as high as possible ($>$ 0.7 Hz) by splitting data-flow into 4 parallel streams, one per TPC chamber, afterwards combined once consistency has been checked.

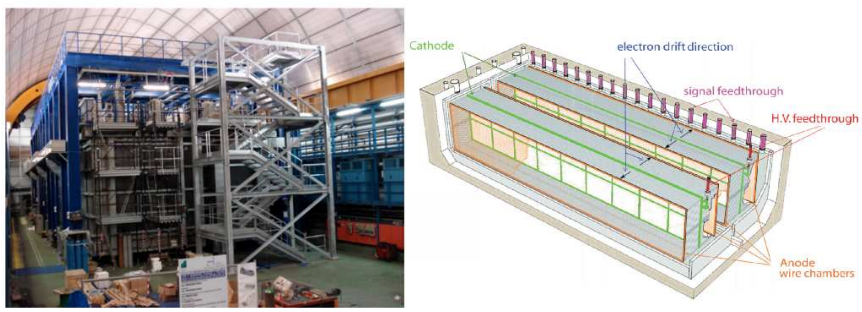

Fig. 1. The ICARUS T600 detector in Hall B at the LNGS underground laboratory (left) and a simple sketch of the inner TPCs structure (right).

Scintillation light detection allows to determine the absolute time of the ionizing events. For this purpose arrays of Photo Multiplier Tubes (PMTs), operating at the LAr cryogenic temperature[3] and made sensible to VUV scintillation light (= 128 nm) by applying a wavelength shifter layer (TPB), are installed behind the wire planes.
In ICARUS T600 detector an elaborate cryogenic plant allows to reduce and keep at an exceptionally low level the electro-negative impurities, especially water and Oxygen, filtering both LAr and GAr with Oxysorb/Hydrosorb filters. The electron lifetime is monitored by studying the attenuation of the charge signal as a function of the drift time along "clean" through-going muon tracks in Collection view. With the liquid recirculation turned on, the free electron lifetime (τ_e) is constantly above 6 ms in both cryostats (Fig. 2); this corresponds to 0.05 ppb O_2 equivalent impurity concentration, producing 16% charge attenuation at the maximum 1.5 m drift distance.

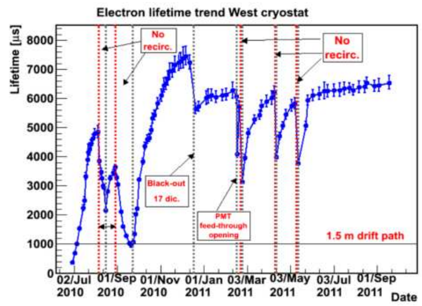

Fig. 2. Free electron lifetime evolution with time in 2010-2011 run, for both cryostats.

1.2. *Trigger strategy*

The main ICARUS T600 trigger system relies on the scintillation light signals, using the analog sum of signal from PMTs with a $\sim$ 85 photo-electron discrimination threshold for each of the four TPC chambers.

(i) For CNGS neutrino events $\sim$ 60 μs gate is open at the predicted proton extraction time, (”early warning” signal sent from CERN to LNGS 80 ms before the extraction); a trigger is generated when the PMT sum signal is present in at least one TPC chamber within the gate. About 80 events/day are recorded (1 mHz rate), well distributed in the 10.5 μs proton spill width.

(ii) For cosmic rays an efficient reduction of the spurious signals, still maximizing the detection of low energy events, is provided by the coincidence of the PMT sum signals of the two adjacent chambers in the same module, relying on the 50% cathode transparency. A trigger rate of $\sim$ 18 mHz per cryostat has been achieved leading to about 100 events/hour on the full T600 (expected: 160 events/hour), out of which only 6% are empty. Recently the PMTs HV biasing system has been upgraded in order to increase the c-ray detector efficiency.

Performance of the trigger system can be pushed forward by using the charge information. A new dedicated DR-slw algorithm, able to online identify hits with 1 board (32 wires) modularity,[4] has been software implemented since May 3^{rd} in an independent 2-levels trigger for CNGS events. Events are collected at 200 mHz rate every time the CNGS gate is opened, and empty events are rejected in real time at 10^4 level. The same algorithm is being hardware implemented to trigger on low energy localized events.

2. Physics programme

The main goal of the ICARUS T600 programme[5] is the search for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the CNGS beam, i.e. an almost pure ν_μ beam with $E_\nu \sim$ 17.4 GeV, traveling over 732 km from CERN to Gran Sasso. Particulary attractive is the $\tau \rightarrow e\nu\nu$ channel where kinematical selection criteria based on missing transverse momentum allow to fully reject with 50% efficiency the associated background. On the same beam the search for sterile neutrinos in LNSD parameter space is also performed, looking for an excess of ν_e CC events. ICARUS T600 is studying also atmospheric neutrinos.
Finally, thanks to the powerful background rejection and its 3×10^{32} nucleons, ICARUS T600 can play a role in proton decay search, in particular in interesting exotic channels not accessible to Čerenkov detectors.

3. 2010–2011 data taking and analysis with CNGS beam

ICARUS-CNGS run started in stable conditions on October 1^{st}, collecting $5.8 \cdot 10^{18}$ pot out of the $8 \cdot 10^{18}$ delivered by CERN up to November 22^{nd}. The CNGS beam restarted on March 19^{th} 2011: $3.9 \cdot 10^{19}$ pot have been collected up to September 30^{th} out of the $4.2 \cdot 10^{19}$ pot delivered, with detector duty cycle in excess of 93%. Data collected in 2010 run have been used for training and tuning the analysis software tools. 169 neutrino events have been identified, into 434 t fiducial volume, in good agreement with the expectations (172) accounting for fiducial volume and DAQ dead-time.

- Momentum of long μ tracks is determined by multiple scattering with a Kalman filter algorithm[6] with $\sim$ 16% resolution. The resulting spectrum is in good agreement with expectations (Fig. 3 left).
- All tracks are fully 3D reconstructed using a polygonal line algorithm[7] and particles (mainly μ, π, K and p) are identified with a neural network approach by studying the event topology and the energy deposition per track length unit as a function of the particle range (dE/dx versus range).
- Electrons, identified by the characteristic e.m. showering, are well separated from π^0 by γ reconstruction, dE/dx signal comparison and π^0 invariant mass measurement.[8] This guarantees 90% efficiency identification of the leading ν_e CC e^-, while almost fully rejecting NC interactions.

Besides the event-by-event approach, the calorimetric energy measurement of the CNGS ν_μCC events has been performed: leptonic and hadronic part have been separately reconstructed, and MC has been corrected for non-containment and non-compensation (Fig. 3 right).

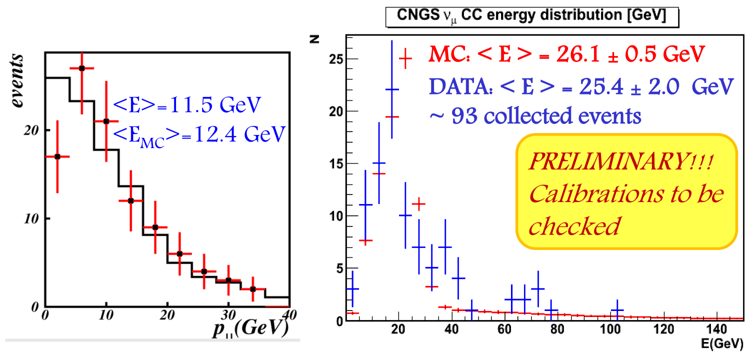

Fig. 3. Muon momentum recontructed by multiple scattering (left) and ν_μCC energy spectrum (right) compared with MC expectations

4. Conclusions

The ICARUS T600 LAr-TPC, installed underground @ LNGS, has been succefully collecting CNGS ν_μ events since October 2010, searching for $\nu_\mu \to \nu_\tau$ oscillation and LSND-like ν_e excess, studying atmospheric neutrinos and exploring the nucleon stability in few selected channels.
While the 2011 data taking is smoothly going over, the analysis of the 2010 CNGS events demonstrated unique imaging capability, spatial and calorimetric resolutions of the LAr-TPC technique.

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