Vol. 42 (2011) ACTA PHYSICA POLONICA B No 11

# UNDERGROUND OPERATION OF THE ICARUS T600 DETECTOR IN GRAN SASSO LABORATORY*

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*(Received October 18, 2011)*

The multipurpose ICARUS T600 detector, with its large sensitive volume, high granularity, excellent tracking and particle identification capabilities, is an ideal device for searching for phenomena beyond the Standard Model. The ICARUS T600 addresses a wide physics program. It is simultaneously collecting a wide variety of "self-triggered" events of different nature, such as cosmic ray events (atmospheric and solar neutrino interactions), and neutrino interactions associated with the CNGS neutrino beam. It will also search for rare events, like a proton decay.

DOI:10.5506/APhysPolB.42.2399
PACS numbers: 29.40.–n, 29.40.Gx, 95.55.V

## 1. Introduction

The Liquid Argon Time Projection Chamber (LAr-TPC), first proposed by Rubbia in 1977 [1], is a powerful detection technique that can provide a 3D imaging of any ionizing event. LAr-TPC provides excellent calorimetric measurements of particle energy. The ICARUS T600 is installed in the Hall B of the Gran Sasso underground National Laboratory (LNGS) of Istituto Nazionale di Fisica Nucleare (INFN), shielded against cosmic rays by 1400 m of rock. The description of ICARUS T600 detector and its underground operation in 2010 are presented in this paper. A fully reconstructed neutrino interaction collected by T600 will be discussed.

* Presented at the XXXV International Conference of Theoretical Physics "Matter to the Deepest", Ustroń, Poland, September 12–18, 2011.

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## 2. The ICARUS T600 detector

The ICARUS T600 detector [2] consists of a large cryostat split into two identical, adjacent and independent half-modules, with an overall volume of about 760 tons of ultra-pure liquid argon at temperature of 89 K. Each half-module houses two TPCs separated by a common cathode. The anode of each TPC is made of three parallel wire planes, 3 mm apart, oriented at 0° and ±60° with respect to the horizontal direction. The operational principle of the LAr-TPC relies on ionization electrons that can be transported practically undistorted by the application of an uniform electric field ($E_D = 500$ V/cm) over macroscopic distances — see illustration in Fig. 1. The signals coming from each wire are continuously read and

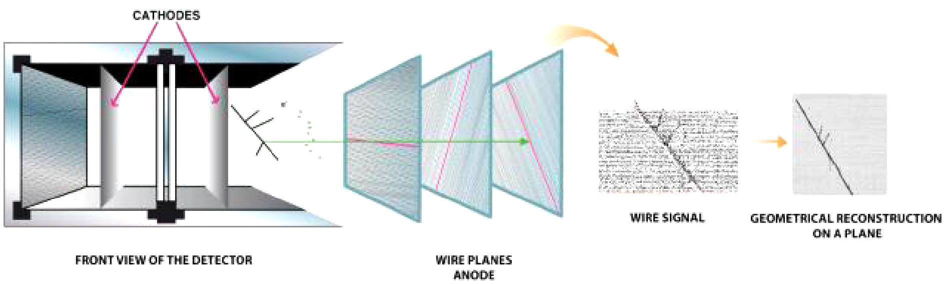


Fig. 1. Illustration of the ICARUS T600 working principle: a charged particle ionization path in LAr and its geometrical reconstruction on a plane.

recorded in multi-event circular buffers. The measurement of the absolute time of the ionizing event, combined with the electron drift velocity information ($v_D \sim 1.6$ mm/$\mu$s at $E_D = 500$ V/cm), provides the absolute position of the track along the drift direction. The determination of the absolute time of ionizing event is accomplished by the prompt detection of the scintillation light produced in LAr by charged particles. For this purpose arrays of Photo Multiplier Tubes (PMTs) are installed behind the wire planes. The PMTs are coated with wavelength shifter to allow the detection of VUV scintillation light ($\lambda = 128$ nm) and they are operating at the LAr cryogenic temperature [3].

### *2.1. LAr purity*

The detector imaging capability and a correct estimation of the energy deposition from the ionization charge signal relies on a liquid argon purity. Purity is continuously monitored measuring the charge attenuation along ionizing clean through-going cosmic muon track. The drifting electrons, before they reach the anode planes can be captured by the electronegative contaminants (mainly $O_2$, $H_2O$ and $CO_2$). With the liquid recirculation turned on, the LAr purity steadily increased, reaching values of free electron lifetime[1] ($\tau_e$) exceeding 6 ms in both cryostats (Fig. 2). Pump maintenance required some stops of the LAr recirculation lasting several days which resulted in a degradation of the purity suddenly recovered as soon as pumps were back on. The $\tau_e$, however, never dropped below 1 ms.

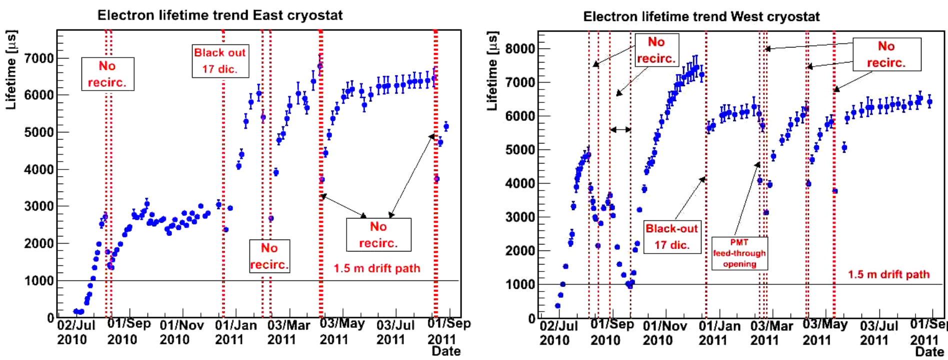


Fig. 2. Free electron lifetime monitoring in East (left) and West (right) cryostats as a function of the elapsed time.

### *2.2. CERN Neutrinos to Gran Sasso — CNGS*

The CNGS project aims at directly detecting $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations. A muon–neutrino beam ($10^{17}\,\nu_\mu$/day) is generated at CERN and directed towards the Gran Sasso National Laboratory, 732 km away. A beam of this type is generated from collisions of protons in a beam with nucleons in a graphite target. The products of such interactions (mostly pions and kaons) are not stable particles. In most of the cases they decay to $\nu_\mu$ neutrinos and muons. The muon–neutrino energy spectrum is the key feature for the ICARUS T600 experiment. The average muon–neutrino energy is $\sim 17$ GeV/$c$.

The trigger system relies on the scintillation light signals provided by the internal PMTs and on the SPS proton extraction time for the CNGS beam. For every CNGS cycle two proton spills, lasting 10.5 $\mu$s each, separated by 50 ms, are extracted from the SPS machine (Fig. 3). An 'early warning' packet is sent from CERN to LNGS 80 ms before the first proton spill extraction. The discrimination thresholds for the PMT sum signals have been set at a threshold around 85 phe. for both, West and East half-modules, during a 60 $\mu$s spill gate in coincidence with each CNGS extraction. The

[1] Free electron lifetime is the average capture time of a free ionization electron by an electronegative impurity in LAr. It can be expressed as $\tau_e\,[\mathrm{ms}] \sim 0.3/N\,[\mathrm{ppb}]$, $N$ being the oxygen equivalent impurity concentration.

CNGS-type trigger is generated when a signal from the internal PMTs of a TPC chamber is present within the CNGS gate. As a result about 80 events per day are recorded with a trigger rate of about 1 mHz. The analysis of the recorded neutrino interactions in LAr, shows synchronization between ICARUS T600 and the actual proton extraction time (Fig. 3). The residual 2.4 ms delay is in agreement with the neutrino time of flight (2.44 ms) taking into account the timing signal propagation dalay to Hall B ($\sim 44\,\mu$s).

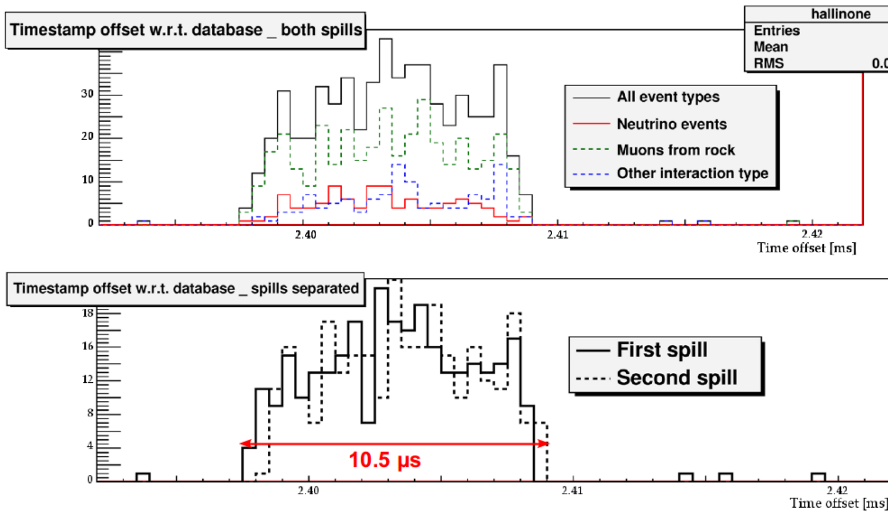


Fig. 3. Time distribution of the recorded neutrino interactions in the T600 with respect to the CNGS proton extraction time. Top: according to event classification, bottom: separately for first and second CNGS spill.

### *2.3. CNGS data taking*

The CNGS run 2010 started in stable conditions on the 1st of October and continued till the beam shutdown, on the 22nd of November.

In this period $5.8 \times 10^{18}$ p.o.t. were collected out of $8 \times 10^{18}$ p.o.t. delivered by CERN (left plot in Fig. 4), with the detector lifetime up to 90% since November 1st. ICARUS T600 detector smoothly started data taking on March 18th, 2011 receiving the CNGS neutrino beam operating in high dedicated mode. In the time interval from the 18th of March to the 28th of August CNGS delivered $3.74 \times 10^{19}$ p.o.t. (right plot on Fig. 4). The detector lifetime in this period was about 93%, allowing the collection of about $3.46 \times 10^{19}$ p.o.t.

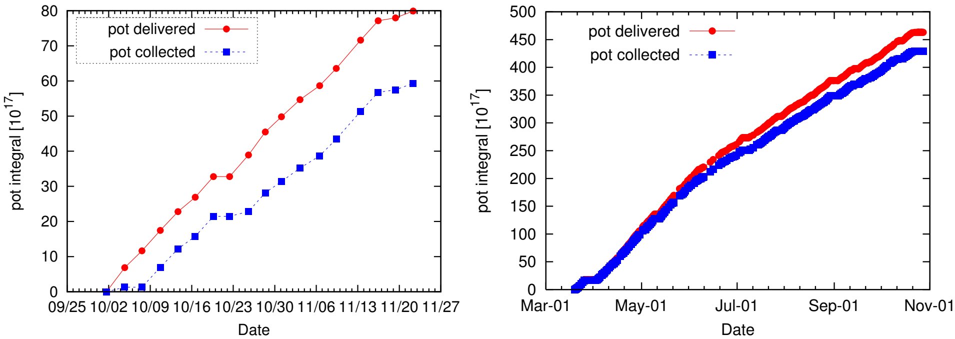


Fig. 4. Number of p.o.t. collected by ICARUS T600 during 2010 (left) and 2011 (right) compared with the beam intensity delivered by CERN.

## 3. Neutrino events

The T600 at LNGS is detecting neutrino interaction events both from the CNGS beam and from cosmic interactions. The software for event visuallization and reconstruction is an evolution of what was originally developed for the ICARUS T600 test run held in Pavia in 2001 [4]. The 3D track reconstruction starts from a 2D track finding algorithm based on an automathic clustering over an angle-position matrix [5]. An approach based on principal curve analysis has been developed for three dimentional reconstruction [6]. The information from track reconstruction fed the algorithms for muon momentum determination through multiple scattering, and for particle identification through neutral networks trained on the shape of the $dE/dx$ energy behaviour. A shower measurement algorithm providing the reconstruction of shower geometry, initial $dE/dx$ and total energy has been developed on MC and is being validated with real data. The available analysis tool allow a complete kinematical reconstruction of the neurino interactions.

An example of CNGS NC event is shown in Fig. 5. The use of two different views allows the recongnition of the presence of two distinct electromagnetic showers pointing to the primary vertex. The corresponding conversion distances are measured to be 12 cm and 26 cm respectively. The invariant mass $m^*_{\gamma\gamma} = 512 \pm 48$ MeV$/c^2$, associated with electromagnetic showers, compatible with the $\eta$ particle mass, is determined, under the assumption of equally shared energy between the two photons, from their opening angle $\theta = (44.5 \pm 2.5)^\circ$ and the total energy $E_{\rm tot} = 2126 \pm 56$ MeV. In the primary vertex one can see also a pion decaying in rest into muon (which track is not visible due to very low value of energy). Thereafter, the muon decays into electron with visible track. The energy deposition for pion was measured to be $137 \pm 12$ MeV, and for electron to be $35 \pm 3$ MeV.

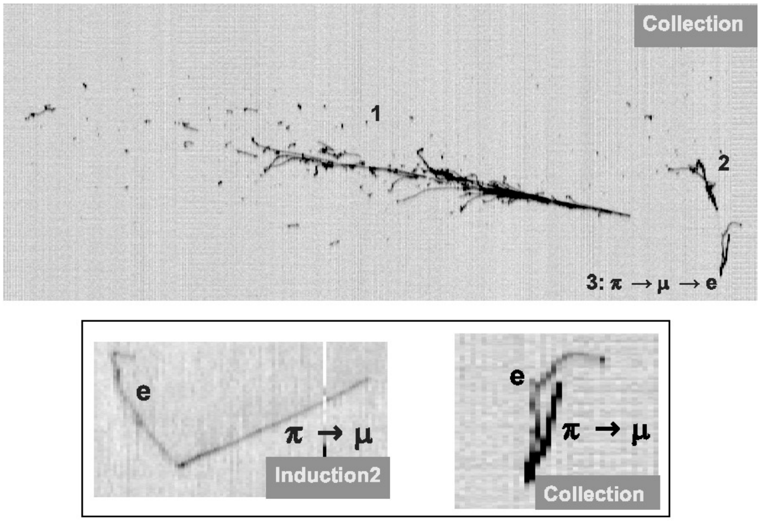


Fig. 5. An example of NC neutrino interaction with $\eta$ particle created in the primary vertex in Collection view (top); close-up view of the pion decay in primary vertex in Induction2 and Collection projection (bottom).

## 4. Conclusions

The ICARUS T600 detector is, so far, the biggest LAr detector ever built. It has been successfully installed in the Gran Sasso underground National Laboratory (Italy) and, after having smoothly reached the optimal working conditions, it is presently collecting data for its second year of CNGS neutrino beam. ICARUS T600 represents the final milestone of a series of fundamental technological achievements in the last several years. Its underground operation demonstrates that T600 technology is mature and scalable to much larger masses, in the range of tens of kton, as required to realize the next generation experiments for neutrino physics and proton decay searches. The examples of neutrino interaction event preliminary analyzed in this paper show that reconstruction precedures and particle identification are correctly performed, fully exploiting the physical potentiality of this technology.

This work has been partially supported by the Polish Ministry of Science and Higher Education under grant number N N202 064936.

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