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THE ICARUS EXPERIMENT AT THE GRAN SASSO UNDERGROUND LABORATORY* **

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The present ICARUS detector, called T600, is ready for installation in the Gran Sasso underground laboratory. It consists of two large cryostats, each one filled with 300 tons of Liquid Argon and equipped with two Time Projection Chambers (TPCs). An overview of the T600 detector is given. Main results of the analyses of the data collected during the surface tests with cosmic rays in summer 2001 are presented. They illustrate the detector's excellent performance. A vast physics program of the ICARUS experiment, which includes different aspects of the neutrino studies and searches for proton decays, is shortly discussed. Finally, the detector upgrade towards the total mass of 3000 tons of Liquid Argon is mentioned.

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1. Introduction

The ICARUS experiment [1] will be realized at Gran Sasso, in the world's largest underground laboratory. It is located under 1400 meters of rock and is accessed from the tunnel of the Roma–Teramo highway. There are three big experimental halls and a number of galleries and small chambers. The ICARUS detector will be placed in hall B.

The ICARUS detector is based on the concept of large TPC chambers filled with Liquid Argon (LAr), originally proposed by C. Rubbia [2] and for many years being developed in Italy. Due to its fine granularity the

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detector reaches a similar precision in track reconstruction as the old-days heavy liquid bubble chambers. Hence the ICARUS detector is often called "the electronics bubble chamber".

The current ICARUS detector, named T600, consists of two cryostats, each one containing 300 tons of Liquid Argon and being equipped with two TPC chambers. They have been constructed, commissioned and tested in Pavia by the end of 2002. The T600 detector with one cryostat fully equipped in TPC chambers and read-out electronics passed successfully the surface tests with cosmic rays during summer 2001. These tests made evident the maturity of the ICARUS technology and an excellent physics performance. The T600 principle of operation, overall design, main components and test results are described in Section 2.

The ICARUS experiment, due to its fine detector, can realize a vast physics program. It includes studies of the neutrino interactions and oscillations for solar, supernova, atmospheric and accelerator neutrinos as well as searches for the proton decay. A short description of these interesting studies is given in Section 3.

Accuracy and sometimes even feasibility of measurements depends on the total mass of the detector. Plans for the upgrade of the present ICARUS detector are presented in Section 4.

2. ICARUS T600 detector

The detailed description of the design, construction and tests of the present ICARUS T600 detector can be found in [3]. The detector got approved and funded in 1996 and had been built between years 1997 and 2002. Its construction followed the period of more than a decade of the extensive R&D programme realized with prototype detectors of different size. Among others, the programme included proving the detector operation principle, demonstrating the feasibility of different technological aspects, *e.g.* Liquid Argon purification or signal processing and developing the imaging, simulation and reconstruction programs based on the data collected during various tests.

The T600 installation plan in the Gran Sasso laboratory, including the safety risk analysis, has been completed in year 2003. The detector is ready for the transportation from Pavia to Gran Sasso. The time depends on the authorities of the laboratory.

2.1. Operation principle

A simplified illustration of the LAr TPC operation principle is given in Fig. 1. A charged particle, traversing a volume of Liquid Argon, interacts with Argon atoms causing their ionization and the emission of scintillation light. A very fast signal (5 ns) of the scintillation light (128 nm) can be used for triggering purposes and for an event absolute time determination. The much slower ionization signal serves for imaging of particle tracks. About 8000 electron-ion pairs per mm of particle path in LAr are produced in the case of minimum ionizing particle. Some of them recombine. Remaining ionization electrons drift toward anode wire planes under the action of a uniform electric field generated between electrodes placed at different electric potentials. In the ICARUS T600 detector the voltage difference equals 75 kV, corresponding to an electric field of 500 V/cm for the 1.5 m distance between the electrodes. The maximum drift time is equal to about 1 ms.

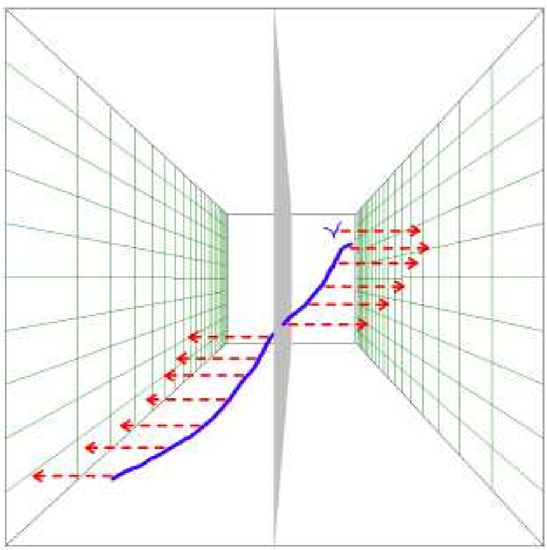

Fig. 1. Principle of the charged particle imaging in the Liquid Argon TPC.

In order to avoid attenuation of the drift electron signal over drift distances of meters the LAr must be extremely pure; the contamination level of electro-negative impurities has to be kept below 0.1 ppb of O_2 equivalent.

There is no amplification of the electron signal in the detector. The anode, placed at the end of the drift distance, is a wire grid formed by at least two parallel wire planes with different wire orientations (see Fig. 1). In the T600 detector there are three planes of wires; at 0°, +60° and −60° w.r.t. horizontal. The distance of 3 mm is kept between the neighboring wires in the plane and between the neighboring wire planes. The first two planes on the way of drifting electrons are undisturbing for electrons. The signal, proportional to the drift electron total charge, is induced on the wires due to the charge movement. The third wire plane works in the collection mode, *i.e.* the drifting electrons are collected on the wires.

The ICARUS detector is continuously sensitive. The read-out electronics measures signal amplitudes on each wire as functions of time, by probing the amplitudes every 400 ns. So that each wire plane gives a two-dimensional projection of an event image with one coordinate corresponding to the wire position and the other to the drift distance. The drift distance is the same for all three projections of a given small space element of the TPC chamber. Thus, one obtains a three-dimensional image of an event by correlating signals from two projections at the same drift distance. The third plane serves for improving the reconstruction quality, *i.e.* pattern recognition, resolution and efficiency.

The size of a single 3-dimensional "bubble" in the ICARUS detector is $(3 \times 3 \times 0.6)$ mm^3. It is comparable to bubble sizes in heavy liquid bubble chambers like the Gargamelle chamber, famous for the discovery of neutrino interactions mediated by neutral currents. The small bubble size together with a good signal/noise ratio (about ten) leads to very good event imaging and, as a consequence, to a very good spatial resolution in particle track reconstruction, very good calorimetric measurements and to a considerable background reduction, all three essential in studies of very rare physics phenomena.

2.2. Detector overview

An idea of the overall structure of the ICARUS T600 detector is sketched in Fig. 2. The detailed description of the detector together with many photos of the components can be found in [3]. Here I give only a short introduction to further reading.

The T600 detector consists of two cryostats, each of them having the internal dimensions of 3.6 m (width) $\times$ 3.9 m (height) $\times$ 19.6 m (length) and being constructed out of Aluminum profiles and panels. A common thermal insulation, mostly made of Nomex honeycomb structures about 0.5 m thick, surrounds the cryostats. Each cryostat houses the inner detector composed of two TPC chambers, the field shaping system and other instrumentation, like photo-multipliers (PMTs) to detect the scintillation light, different monitors and probes of the slow controls system. The purity monitors, developed by the ICARUS collaboration, are of special interest. They allow a determination of the LAr contamination at a level below 0.1 ppb of O_2 equivalent.

There is one cathode plane per cryostat, common for the two TPC chambers. It is made of perforated stainless steal plates and is placed centrally along the long side of the cryostat. Thus the cathode divides the whole volume into two symmetric parts. The two wire chambers, each composed of three planes of wires, are parallel to the cathode and are placed symmetri-

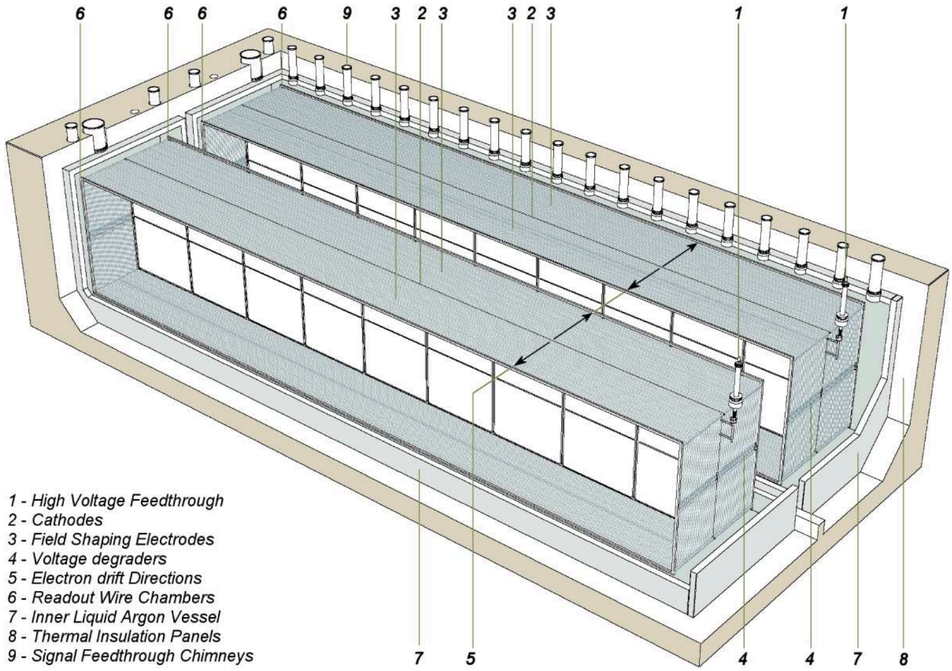

Fig. 2. Schematic presentation of the T600 detector.

cally at a distance of about 1.5 m, close to the side walls. The first plane (as seen by the drift electrons) contains 2112 horizontal wires and is followed by two planes at $\pm 60^\circ$ w.r.t. horizontal, each containing 5600 wires. The first and the second wire planes work in the induction mode, while the third one collects the electrons. The sensitive mass of LAr, *i.e.* LAr inside volumes limited by the wire chambers, equals 476 tons (as compared to the total mass of 600 tons of LAr).

Three customize electronics boards have been produced by CAEN for the ICARUS detector read-out purposes [3]. The decoupling board receives analog signals from the TPC wires through vacuum tight feed-through flanges and passes them to the analog board. The latter performs signal amplification, 16:1 multiplication and ADC conversion at a 40 MHz rate. The digital board performs the zero-signal suppression by applying a hit finding algorithm executed in the programmable DAEDALUS chips. The amount of data corresponding to a single full size event is equal to about 226 Mbytes, hence the on-line data reduction is a necessity.

Externally the T600 detector is completed by the cryogenic plant composed of a cooling circuit to maintain constant the LAr temperature and of a system of LAr purifiers to keep the LAr purity at the required high level.

2.3. Surface tests with cosmic rays

The hundred-days long surface tests with cosmic rays, performed in summer 2001 with the fully operational first half of the T600 detector, had demonstrated the maturity of the ICARUS technology at the kton scale.

The main phases of the test run included ten days of vacuum pumping (down to 10^{-3} mbar or less) in order to clean up the major part of electronegative impurities collected during the detector assembly, two weeks of the cryostats cooling (down to -125° on average), ten days of filling with LAr and 68 days of voltage setting, read-out debugging and data taking with cosmic rays. The detector passed all these phases extremely well. For example, no single wire got broken and no non linear behavior of the cryostat wall displacements as a function of pressure was observed.

About 28000 triggers, equivalent to about 4.5 Tbytes of data, had been collected during tests. The trigger system was based on the signals from external scintillator planes or/and on the signals from PMTs immersed in LAr. The collected event topologies were: long horizontal muon tracks (requested by the scientific committees), bundles of vertical muons, stopping and decaying muons, electromagnetic cascades initiated by photons, electrons and very energetic muons as well as hadronic interactions. To illustrate the quality of the data, Fig. 3 shows a hadronic interaction with charged hadrons and photons from π^0 decays in the final state. Many other examples are given in [3].

2.4. Detector performance

The T600 tests of year 2001 showed that such technological challenges like cryogenics, argon purification, high voltage for the drift, collection of the scintillation light, read-out and data acquisition systems as well as collection and visualization of a big amount of data can be successfully overcome. Analyses performed on the collected data provided further justification for the detector's excellent performance. The results, which have already been published, include:

- Observation of long tracks (up to 18 m) produced by the horizontal muons [4], illustrating the proper functionality of the detector over the whole volume and of the read-out electronics.

- Detection of Cherenkov light emission in LAr [5]. This interesting observation was mostly based on the data from the largest, 14 ton prototype detector, where the quartz windowed PMT was installed. Therefore, the detection of any light, *e.g.* the Cherenkov photons, except the copiously produced 128 nm scintillation light of LAr was allowed.

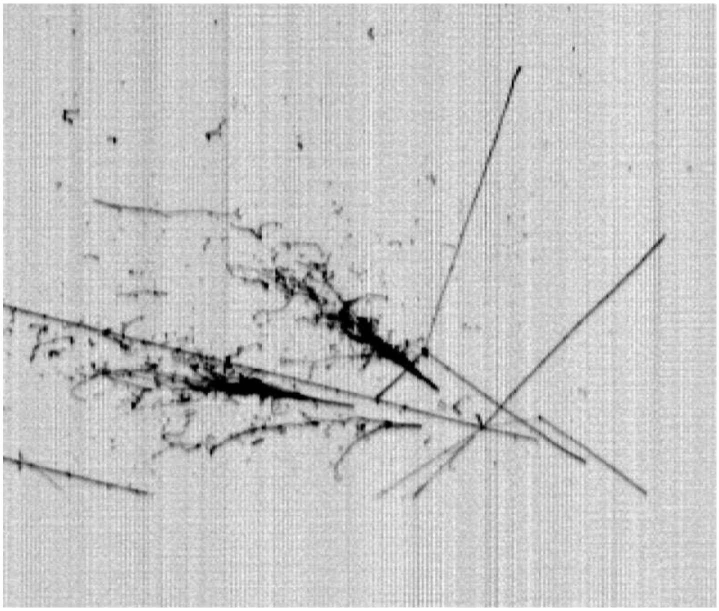

Fig. 3. Hadronic interaction in the T600 detector; run 705, event13.

- Analysis of the LAr purity [6] based on two complementary techniques: measurements performed with the purity monitors (localized in space) and by studying the signals produced by minimum ionizing particles crossing the detector (averaged over a LAr volume). Both methods yielded consistent results. The maximal drift electron lifetime, recorded at the end of data taking, was 1.8 ms and showing no saturation.

- Study of electron recombination in LAr [7] as a function of the applied drift electric field and of the density of the initial ionization. This allowed for a precise determination of the recombination parameter in the Birks function. The analysis was based on the data from both the T600 detector and the small three ton prototype.

- Determination of the Michel parameter ρ [8] based on the measurement of the μ decay energy spectrum for 1858 μ decays. This first physics result from the ICARUS detector was obtained with a non optimized experiment and yielded $\rho = 0.72 \pm 0.06$ (stat.) ± 0.08 (syst.) as compared to the value 0.75 predicted by the Standard Model. The achieved accuracy, comparable with that of the LEP experiments measuring τ decays, shows the capabilities of the ICARUS detector to obtain reliable physics results.

3. Physics program

The physics program of the ICARUS experiment concerns two big issues in particle physics: studies of neutrinos and searches for proton decays. In both cases the achievable sensitivity of the ICARUS detector for different measurements depends on the detector's total mass. As shown in [9], some valuable results can already be obtained after two years of running with the present detector.

Other important factors defining the detector's sensitivity are the granularity and the resolution for calorimetric measurements. For both the LAr TPC technique offers an excellent performance leading to a strong background rejection, precise track reconstruction and accurate $\frac{dE}{dx}$ measurements. The outcome is that for many measurements the sensitivity of the LAr TPC is comparable to that of the water Cherenkov detector with a ten times bigger mass. One should remember that the experiments, like Super-Kamiokande and SNO are running and continuously taking data, while the ICARUS schedule is not completely clear. Hence in the following I will concentrate on the discussion of the qualitative improvements brought by the ICARUS measurements as compared to measurements by the other experiments.

3.1. Neutrino interactions and oscillations

The ICARUS experiment will perform studies of the solar, supernova and atmospheric neutrinos, as well as of the accelerator neutrinos from the CNGS beam [10].

The ICARUS analysis of the solar and supernova neutrinos is characterize by two types of measured processes namely: elastic scattering on atomic electrons and absorption of neutrinos. The LAr TPC is the only detector distinguishing the signal of electron neutrinos from the signal of electron antineutrinos due to their different absorption by Argon. It is a very important feature for studies of the supernova neutrinos.

The ICARUS analysis of the atmospheric neutrinos will be performed for an enlarged event sample as compared to the Super-Kamiokande. First, for the charge currents (CC) ν_μ and ν_e interactions, all the final states and low energy neutrinos will be included into the analysis. In the Super-Kamiokande experiment most of the analysis is performed for the final states with a single charged lepton, requiring moreover that its energy be above 400 MeV. Second, the neutral current (NC) atmospheric neutrino interactions will be analyzed as well. One should also stress the excellent identification of electrons in the final state. All that leads to an unbiased, systematics-free event sample and an improved reconstruction of the neutrinos energy and direction.

Studies of the accelerator neutrinos from the CNGS muon neutrino beam from CERN to Gran Sasso [10] should start in 2006 and take five years, corresponding to 2.25×10^{20} protons on target in total. ICARUS will analyze the following processes:

- ν_μ CC interactions: to study the ν_μ beam characteristics,
- ν_τ CC interactions: to search for $\nu_\mu \to \nu_\tau$ dominant oscillations,
- ν_e CC interactions: to search for $\nu_\mu \to \nu_e$ subdominant oscillations and study the beam contamination with ν_e-s,
- ν_x NC interactions to search for $\nu_\mu \to \nu_s$ oscillations and to study backgrounds.

The direct, background-free observation of the ν_τ appearance in the ν_μ beam is the primary goal of the CNGS experiments ICARUS and OPERA. The search for the subdominant oscillations $\nu_\mu \to \nu_e$ concerns the most important current measurement in neutrino physics *i.e.* that of the mixing angle θ_{13}.

For the accelerator part of the ICARUS physics program the total detector mass is crucial. Simulations show that the mass of about three kilotons of LAr is needed to get a statistically significant improvement in the determination of the oscillation parameters. For example, with the current best value $\Delta m^2_{23} = 2 \times 10^{-3}$ eV, the expected number of the observed ν_τ interactions is about ten for the whole period of data taking with the 3 ktons detector.

3.2. Searches for proton decay

Proton decays are predicted by the Grand Unification Theories which put fermions and bosons into common multiplets. Several decay modes are searched for by the Super-Kamiokande experiment, the best suited at present for such studies. The gold plated decay channels for this experiment are $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$. These characteristic back-to-back three-ring events are easily recognized in the water Cherenkov detector. The ICARUS total exposure should be of the order of 100 kton$\times$year to reach the present Super-Kamiokande sensitivity. The situation is different for the $p \to K^+\overline{\nu}$ decay channel — the favorite one of the SUSY models. The kaon is not visible in the detector, because it is below the threshold for the Cherenkov light emission is water. Hence the efficiency for the observation of this decay mode is below ten percent and probably even huge water Cherenkov detectors will not help to beat the systematics.

Contrary to the situation at Super-Kamiokande the $p \to K^+\overline{\nu}$ is the gold-plated channel for the ICARUS detector. Measurements of the energy losses along the path of the proton, kaon and its decay products allow for a background-free and almost 100% efficient identification of this decay mode. It means that even a single event would be sufficient to discover this proton decay in the ICARUS experiment.

4. Detector upgrade

For building the 3 kton detector (T3000) the ICARUS collaboration proposed a modular approach, based on the cloning of the T600 detector [1]. This requires the construction of eight additional cryostats, each containing 300 tons of LAr. They will be grouped by four forming two T1200 modules *i.e.* T3000 = T600 + T1200 + T1200. For each T1200 module, two cryostats will be placed on top of the other two.

The proposed design of the new cryostats contains some modifications, fully proven by the T600 technical run in year 2001. Each one will house a single TPC chamber with a cathode close to one long side-wall and an anode wire chamber close to the other. It means that the maximal drift distance will double (3 m instead of 1.5 m), while the total number of wires and electronics channels will halve. This modification is supported by the 2001 tests showing that the drift electron lifetime of 2 ms is easily achieved and the detector stays doubled voltage of 150 kV.

Other modifications, as compared to the T600 detector include using stronger panels for the cryostat construction and a better thermal insulation based on the so called evacuated panels. They will surround each T1200 module. Such panels were placed on one wall of the T600 detector and tested during the technical run.

5. Conclusions

After many years of the R&D program the LAr TPC technology is mature for building the ktons scale detector. This was demonstrated in the T600 technical run with cosmic rays in year 2001. A large amount of data, collected during this run, helped to achieve the big progress in the visualization, full simulation and reconstruction software and to demonstrate the detector's excellent performance for physics, illustrated by the publications [3–8]. The T600 detector is ready for the transportation and installation in the Gran Sasso laboratory, which will hopefully happen this year. The construction of the T3000 detector for the CNGS beam is a very important next step, although extremely challenging from the financial and organizational point of view, also due to requirements for the laboratory infrastructure. As compared to other types of neutrino detectors the LAr TPC detector offers the best sensitivity, per kton of the detector mass, for many measurements, *e.g.* for the θ_{13} mixing angle. A giant LAr TPC detector of 100 ktons [11] could be considered the future tool for precise measurements in neutrino physics and searches of nucleon decays. On the other end of the detector's mass scale (at masses of the order of 100 tons), the LAr TPC could be used as a near detector on the neutrino accelerator beam and, due to its fine granularity, improve the measurements of the beam characteristics as well as of the cross-sections for various neutrino interactions.

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