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Author: Jan Kisiel

Citation style: Kisiel Jan. (2005). Present status of the ICARUS experiment. "Acta Physica Polonica B" (Vol. 36, no. 11 (2005), s. 3227-3234).

Vol. 36 (2005) *ACTA PHYSICA POLONICA B* No 11

PRESENT STATUS OF THE ICARUS EXPERIMENT*

Jan Kisiel

Institute of Physics, University of Silesia
Uniwersytecka 4, 40-007 Katowice, Poland

for the ICARUS Collaboration†

(Received November 2, 2005)

The T600 ICARUS detector, with a mass of about 600 tons of liquid argon (LAr), is the largest LAr Time Projection Chamber (TPC) ever built. It has been successfully tested in Pavia/Italy in 2001. More than 29,000 cosmic rays events have been collected during about 100 days of continuous data taking. It was demonstrated that large mass scale LAr TPC technique is operational. The T600 ICARUS test run results are briefly reported in this paper.

PACS numbers: 29.40.–n, 29.40.Gx

1. Introduction

The LAr TPC was proposed by Rubbia in 1977 [1]. Its operational principle exploits the fact that, in highly purified LAr, ionization charge (electrons) can drift practically undistorted, in an electric field, over distances of meters. The non-destructive readout of electron signals, by subsequent anode wire planes, provides three dimensional imaging of tracks and allows for calorimetric measurements. Many years of the ICARUS Collaboration extensive R&D studies, construction of several prototypes of smaller mass of 50 liters, 3 tons and 14 tons, proved the feasibility of the LAr TPC technique. The successful tests of the cryogenics of the 14 tons LAr resulted in the construction of an 'industrial' T600 module, filled with about 600 tons of LAr. The T600 ICARUS experimental set-up was assembled on the

* Presented at the XXIX International Conference of Theoretical Physics, "Matter to the Deepest", Ustroń, Poland, September 8–14, 2005.

† ICARUS Collaboration: Univ. and INFN of: L'Aquila, Frascati, Gran Sasso, Milano, Napoli, Padova, Pavia, Pisa, IFSI Torino, Politecnico di Milano, ETH Zurich, Univ. of Granada, CERN, Ciemat Madrid, UCLA Los Angeles, Inst. of Nucl. Physics Cracow, Univ. of Technology Cracow, Univ. of Science and Technology Cracow, Univ. of Silesia Katowice, Warsaw Univ., Wroclaw Univ., SINS Warsaw.

Earth surface in Pavia/Italy. All its components (cryogenics, argon purification, high voltage, wire chambers, electronics, data acquisition, ...) have been successfully tested during three months of technical run in 2001. The detailed description of the T600 ICARUS detector design, construction and tests, can be found in [2]. With the use of the LAr technology new important contributions to studies of neutrino signals and matter stability are expected. The physics program of the ICARUS experiment has been presented at many conferences, also in Ustroń/Poland [3]. In this paper a brief description of the T600 ICARUS module and a summary of some results obtained during the 2001 test run are given.

2. The T600 ICARUS detector

The T600 ICARUS detector is composed of two identical half-modules T300 (see Fig. 1). Each of them has internal dimensions of 3.6m (width) $\times$ 3.9m (height) $\times$ 19.6m (length). Each half-module houses two TPCs with common cathode placed in the middle, the electric field shaping system, monitors and probes, and photomultipliers for the LAr scintillation light detection. The external thermal insulation and liquid nitrogen cooling circuit allow to keep the LAr temperature uniform and stable. The LAr purification system completes the detector layout. Along the longest side walls of each half-module three parallel planes of anode wires are located. They are oriented at 60 degrees with respect to each other, 3mm apart, with wire pitch of 3mm. The instrumented volume in the T600 detector is 340.3m^3 (476.5tons) of LAr with the total number of wires equal to 53248. The ionization electrons travel, in an uniform electric field perpendicular to the wires planes, toward them. The maximum electron drift length is 1.5m, whereas the maximum drift time is about 1ms, when the nominal voltage of 75kV is applied. Thanks to an appropriate voltage biasing, the electrons induce a signal on two first *Induction* wire planes, whereas the charge is collected on the last *Collection* plane. This type of read-out allows for a three-dimensional event reconstruction: two-dimensional projections are provided by each pair of wire planes, whereas the position along the drift direction is obtained from the signal timing with respect to the trigger. The prompt detection of scintillation light in LAr defines the time of the event. The Čerenkov light has also been identified during the T600 detector test run [4] in 2001. The LAr purification system [5] was able to keep impurities at a very low level. Therefore, the ionization electrons could drift safely toward the anode wires. The electrons drift life time τ_e has been measured with the purity monitors and with long ionizing tracks. The value of τ_e was increasing during the test run, reaching about 1.8 ms at the end of the data taking, with no sign of saturation. This allows for a drift distance of almost 3m for ionization electrons.

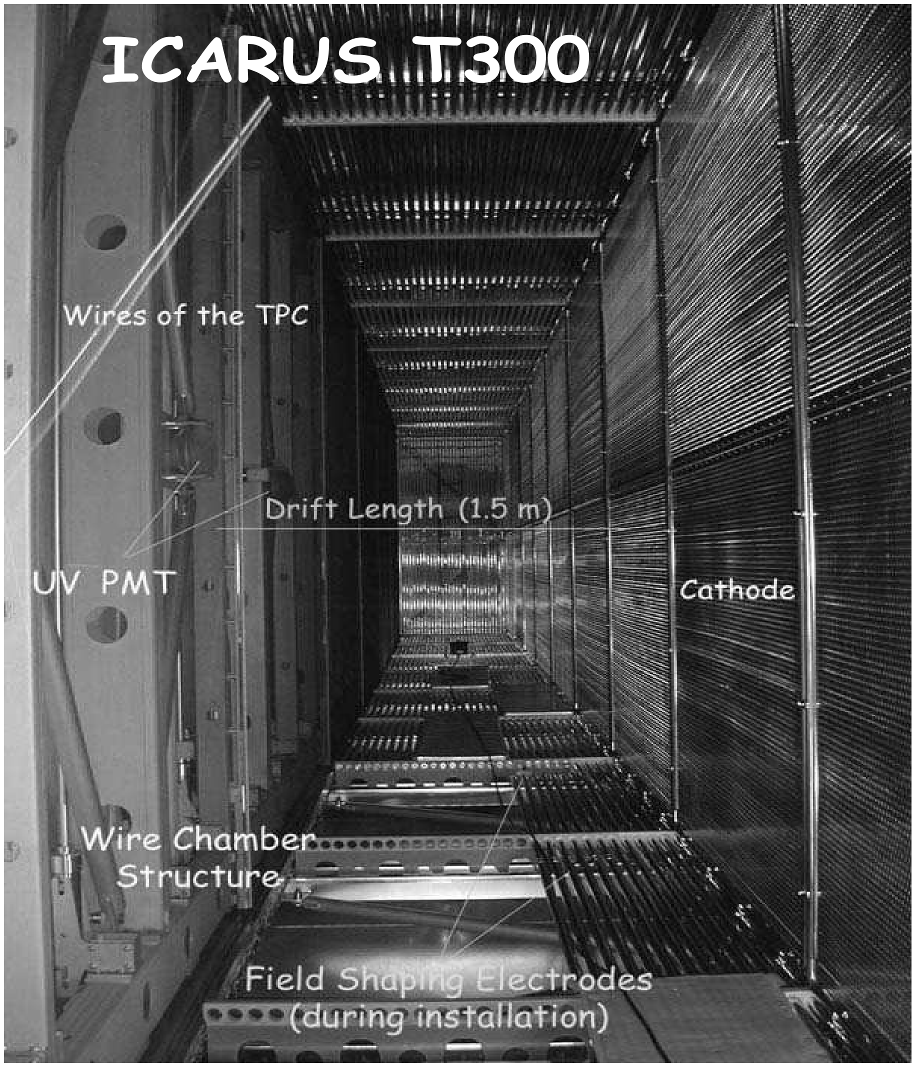

Fig. 1. The inner view of one of Time Projection Chambers (TPC) of the T600 ICARUS module.

More than 29,000 cosmic-ray events have been collected during the test run of the T600 ICARUS detector on the Earth surface in Pavia/Italy in 2001. Some examples, representing selected topologies, are given in Fig. 2. The overall detector performance is illustrated by long (up to 18m) horizontal muon tracks. They were detected with the use of a trigger system made out of two external plastic scintillators working in coincidence. The T600 ICARUS test run data were used at first for the development and optimization of event reconstruction procedures. It was also demonstrated that their analysis can lead to physics results, confirming therefore the capabilities of the ICARUS LAr technique. Different aspects of the T600 ICARUS test run have already been presented in a series of papers [4-7].

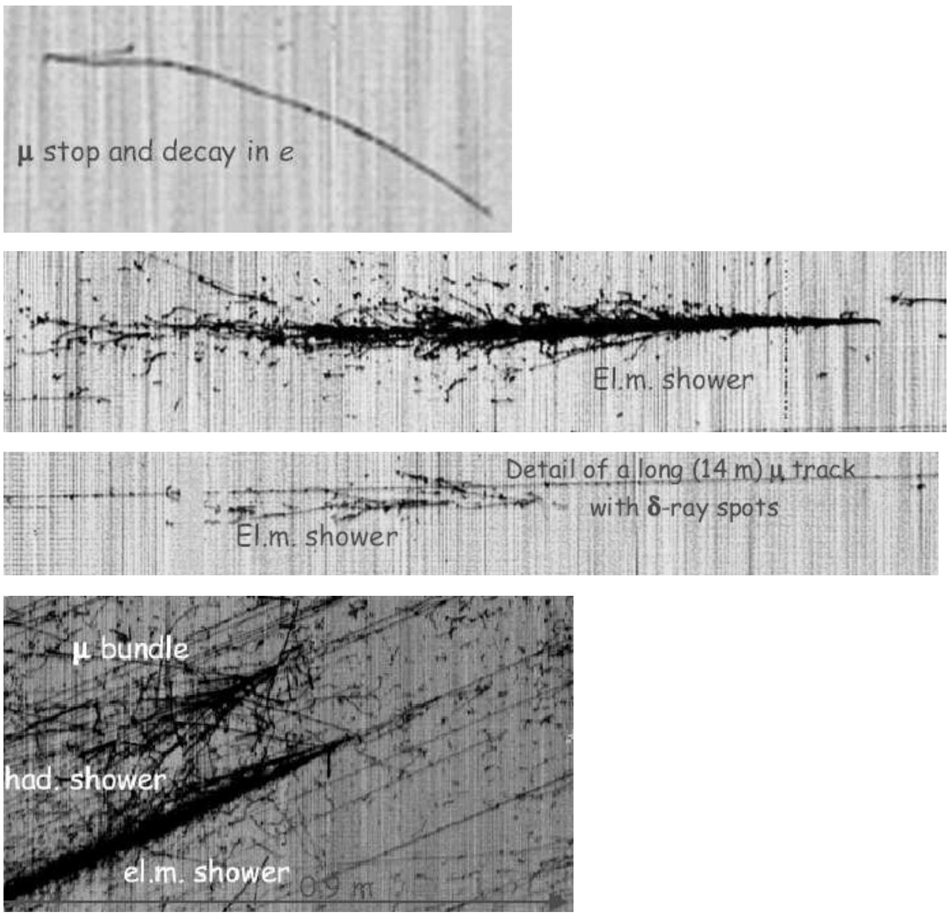

Fig. 2. Examples of cosmic ray induced events collected during the T600 ICARUS test run.

3. Examples of the analysis of the T600 ICARUS data

3.1. Measurement of the μ decay spectrum

The measurement of the μ decay spectrum and the determination of its Michel ρ parameter represent the first physics results obtained with the T600 ICARUS detector. The detailed analysis of the sample of stopping μ

events is given in [7]. Here, only the main steps of the data selection, the event reconstruction and the extraction of Michel ρ parameter are presented. The data selection starts with a visual scanning of the recorded events. The topology of the stopping and decaying μ event consists of two tracks: a minimum ionizing track entering the detector, for which the energy deposition in LAr increases, and a minimum ionizing electron track with length smaller than 23 cm, starting at the end of the first track. Only events with μ and e tracks fully contained in the detector sensitive volume have been accepted.

The T600 ICARUS data reconstruction means a three dimensional, spatial reconstruction of tracks with a subsequent calorimetric reconstruction. The search for wire signals above a local baseline (*hits*) on every wire begins the spatial reconstruction. For each *hit* its position, height and area are calculated. Next, neighboring *hits*, within each wire plane, are grouped together, forming two-dimensional *clusters*. Finally, the three-dimensional position of each *hit* is computed exploiting the fact, that each wire plane constrains two spatial coordinates: one common to all wire planes (the drift coordinate) and one specific to the wire (the wire coordinate). The aim of the calorimetric reconstruction is to determine the deposited energy $E_{\rm hit}$ of each identified *hit*. Summing up all *hit energies* one can obtain the energy of spatially reconstructed track or shower. The $E_{\rm hit}$ is proportional to the: (1) ionization charge which is measured at the collection wire plane, (2) an exponential term involving electron's drift and life times, and (3) calibration and electron-ion recombination factors. All quantities needed to obtain $E_{\rm hit}$ have been extracted from the T600 test run data. The detailed description of the reconstruction algorithm can be found in [2].

The determination of the Michel ρ parameter of the μ decay spectrum was based on the comparison of the measured energy spectrum of electrons from μ decays with the Monte Carlo simulated spectrum. The data sample consisted of 1858 events which passed the reconstruction procedure described above. For all of them, the electron energy lost by ionization had been measured and is represented by dots in Fig. 3. The FLUKA package [8] had been used to generate 10,000 muon decays in LAr. The simulated spectrum, obtained with the Standard Model $V{-}A$ interaction parameters ($\rho = 0.75$ and $\eta = 0$) is presented by solid line in Fig. 3. The best fit to the experimental points (dotted histogram in Fig. 3) gives the following value of the Michel parameter $\rho = 0.72 \pm 0.06 \pm 0.08$, where the first (second) error is statistical (systematical). This value of ρ is in a very good agreement with the $V{-}A$ Standard Model predictions.

Taking the advantage of the excellent agreement between the experimental and simulated μ decay spectra, the energy resolution of the detector for the measurement of electrons of $E < 50$MeV has been determined. The following contributions to the final energy resolution have been taken into

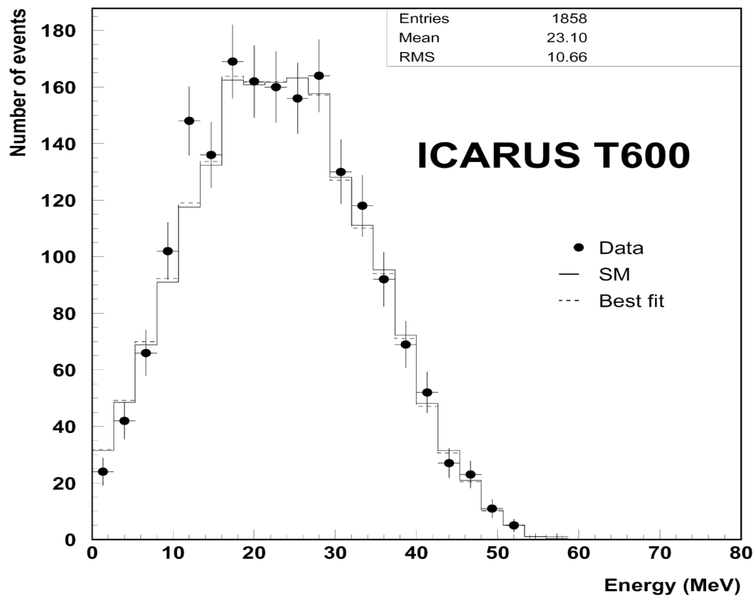

Fig. 3. Energy spectrum of electrons from muon decays in the T600 ICARUS detector. For details see text. Figure taken from [7].

account [7]: reconstruction effects (signal extraction procedure), calorimetric calibration and electronic noise. The first two are energy independent, whereas the last one gives smaller contribution at higher energies. The estimated energy resolution is the following:

$$(E_e^{\mathrm{meas}} - E_e^{\mathrm{MC}})/E_e^{\mathrm{MC}} = 11\%/\sqrt{E[\mathrm{MeV}]} \oplus 2\% \,, \tag{1}$$

where the E_e^{meas} (E_e^{MC}) is the measured (Monte Carlo simulated) energy of the electron track, assuming that electrons loose their energy only by the ionization of Ar atoms.

3.2. Calorimetric measurement of π^0 mass

The CERN CNGS muon neutrino beam will have an unavoidable contamination (about 0.6%) of electron neutrinos. Therefore, in order to measure neutrino oscillation parameters, it is important to distinguish between ν_μ neutral current interactions ($\nu_\mu + n \to \nu_\mu + \pi^0 + X$) and ν_e charged current interactions ($\nu_e + n \to e^- + p$). This requires good identification of electrons and pions. It is not straightforward because, both, the photons from the π^0 decay (π^0 decays in 2γ with a branching ratio of 98.8%) and the electron from the charged current interaction, may initiate an electromagnetic shower. The precision of the measurement of the energy released in LAr by electromagnetic showers can be extracted from the π^0 mass reconstruction. The search for π^0 candidates, produced by cosmic ray induced hadronic interactions in LAr, starts with visual scanning for the following topology: two or more electromagnetic showers pointing to a common vertex of a hadronic interaction.

The calculation of the invariant mass $m_{\gamma\gamma}$ of the $\gamma\gamma$ system

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta_{12})} \tag{2}$$

requires the measurement of the electromagnetic showers' energies E_1, E_2, and the angle θ_{12} between these two gammas. The energy deposited by photons, visible as electromagnetic showers, is evaluated by using the calorimetric method described in the previous section. The angle θ_{12} is obtained from the spatially reconstructed vertex of the hadronic interaction and the starting points of electromagnetic showers. An example of a π^0 candidate is given in Fig. 4. With the reconstructed shower energies $E_1 = 223 \pm 24$ MeV, $E_2 = 350 \pm 43$ MeV, and $\theta_{12} = 29 \pm 1$, the value of 139 ± 13 MeV for the invariant mass $m_{\gamma\gamma}$ was found.

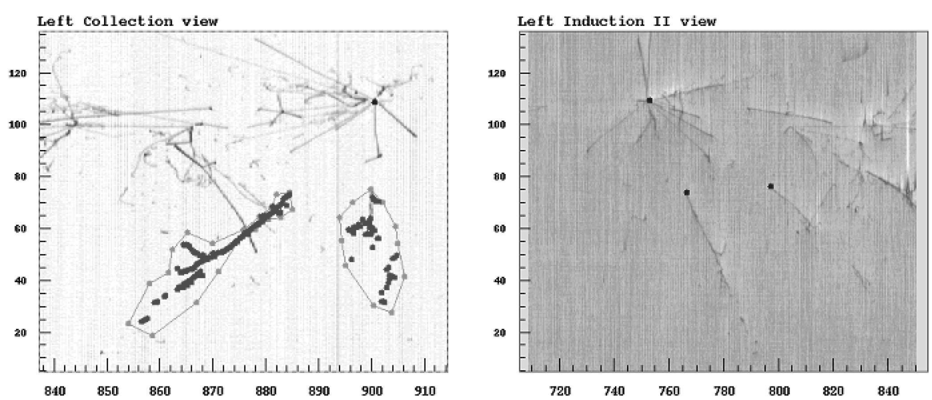

Fig. 4. Two views of an example of a π^0 decay event candidate ('Left' TPC of one of T300 ICARUS half-modules). Energy depositions from electromagnetic showers are marked in the collection view, whereas the interaction vertex and the starting points of electromagnetic showers are visible in both (collection and induction) projections. The horizontal (vertical) axis is in wire (time sample) coordinates (wire pitch 3 mm, one time sample is 400 ns which corresponds to about 0.624 mm drift length).

4. Conclusions

The test run results of the T600 ICARUS detector have been briefly summarized. The analysis of the μ decay spectrum has been discussed. The obtained value of the Michel ρ parameter of the electron energy spectrum is fully compatible with the Standard Model one. The samples of measured and Monte Carlo simulated μ decays were used to determine the energy resolution of the detector for low energy ($E < 50$ MeV) electrons. Also, the calorimetric reconstruction of the $\gamma\gamma$ invariant mass has been presented. It was applied to the π^0 candidate events from hadronic interactions in LAr. This is a method to determine the energy resolution of the detector for the measurements of electromagnetic showers. The analysis of cosmic-ray events validated the method of Liquid Argon Time Projection Chamber (LAr TPC). During the test run it was demonstrated that a large LAr cryostat can work for months giving high quality images of interactions of different types. In December 2004, the T600 ICARUS detector has been successfully transported to the Gran Sasso underground laboratory and is being installed.

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