The ICARUS detector: operation and performance

F. Pietropaolo (INFN Padova) for the ICARUS Collaboration

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The ICARUS Collaboration

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The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event ("electronic bubble chamber") with in addition:

- continuously sensitivity, self triggering capability
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)

**Diagram:**
- Time
- Drift direction
- Edrift ~ 500 V/cm
- m.i.p. ionization ~ 6000 e⁻/mm
- Scintillation light yield 5000 γ/mm @ 128 nm

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Drifting electrons can traverse an arbitrary number of “transparent” wire planes oriented in the direction of the required view. Each of them provides a bi-polar current induction signal. Electrons finally stop on the collection wire plane, inducing a signal proportional to the charge of along the drifting track. A 3D view of the track is obtained matching hits with equal drift times.
The path to larger LAr detectors

   - 24 cm drift wires chamber
   - Laboratory work

   - CERN
   - 3 ton prototype

   - CERN
   - 50 litres prototype 1.4 m drift chamber

   - Icarus T600 experiment
   - 10 m³ industrial prototype

5. 2001: First T600 module
   - Pavia
   - T600 detector

6. Cooperation with industry AirLiquide, Breme, Cinel, CAEN
   - LNGS Hall-B
   - 2010 - ... : Data taking with CNGS beam
The ICARUS detector in underground Hall B of LNGS

- CNGS (CERN $\nu$ to Gran Sasso beam)
  - $\nu_\mu$ NC and CC interactions
  - $\nu_\mu \rightarrow \nu_\tau, \tau \rightarrow e$
  - $\nu_\mu \rightarrow \nu_e \theta_{13}$
  - $\nu_\mu \rightarrow \nu_e$ "LSND"
  - $\nu$ velocity

- Atmospheric $\nu$
- Proton decay

- Major milestone for future LAr detectors
The ICARUS T600 detector

- Two identical modules
  - $3.6 \times 3.9 \times 19.6 \approx 275 \text{ m}^3$ each
  - Liquid Ar active mass: $\approx 476 \text{ t}$
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV  $E = 0.5 \text{ kV/cm}$
  - $v\text{-drift} = 1.55 \text{ mm/µs}$

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at $0, \pm 60^\circ$ (up to 9 m long)
  - $\approx 54000$ wires, 3 mm pitch, 3 mm plane spacing
  - $20+54$ PMTs, 8” Ø, for scintillation light detection:
    - VUV sensitive (128nm) with wave shifter (TPB)

External insulation: evacuated Nomex honeycomb panels
Al LAr containers
Mechanics & Cryogenics

- Wire chamber frame designed for cryogenic environment and transient phases (cooling, warming)
  - None of the wires has to break
  - variable geometry mechanics (springs, rocking frames)
  - High spatial precision (<0.1 mm)
- Slow control devices
  - to work in cryogenic and high purity environment
- Signal feed-throughs
  - vacuum-tight blind-hole DN200CF flanges for 576 ch.
- HV system
  - stable and uniform electric field all over the LAr volume
  - Development of a HV feed-through
  - stable up to -150 kV without discharges and leakage currents, vacuum tightness
  - Field shaping electrodes connected by a cryogenic voltage divider.
ICARUS-T600 @ LNGS: 0.77 kton LAr-TPC

N\textsubscript{2} Phase separator

30 m\textsuperscript{3} Vessels for LN\textsubscript{2} cooling circuit

N\textsubscript{2} liquefiers: 12 units, 48 kW total cryo-power

Electronics ch. (54000)

LAr purification systems

GAr purification systems

LNGS-SC 17 October 2012
ICARUS front-end Electronics (54000 channels)

- Liquid argon
- Gas
- Sense wires (4-9m, 15pF/m)
- Twisted pair cables (~3m, 100pF/m)
- H.V. (±300 V)
- VME board (18/crate)
- Multi-event circular buffer (8x1ms)
- Continuous waveform recording
- To storage

ICARUS preamplifier (WARM)
- Custom IC in BiCMOS technology
- Classical Radeka integrator
- External input stage jFET’s
  - Two IF4500 (Interfet) or BF861/2/3 (Philips) in parallel to increase \( g_m \) (50-60 mS)
- External tunable feed-back network
- External baseline restorer circuit (BW limitation)

- Sensitivity \( \approx 6 \text{ mV/fC} \)
- Dynamic range > 200 fC
- Linearity < 0.5\% @ full scale
- Gain uniformity < 3\%
- E.N.C. \( \approx (350 + 2.5 \times C_D) \) el \( \approx 1250 \text{ el. @ 360pF} \)
- Power consumption \( \approx 40 \text{ mW} \)
The ICARUS read-out chain

Signal UHV feed-through: 576 channels (18 connectors x 32) + HV wire biasing. PATENTED.

CAEN-V789 board: 2 Daedalus VLSI * 16 input channels (local self-trigger & zero suppression) + memory buffers + data out on VME bus

CAEN-V791 board: 32 pre-amplifiers + 4 multiplexers (8:1) + 4 FADC’s (10 bits - 20 MHz)

Decoupling board: HV distribution and signal input

Digital link

FADC’s

Multiplexers

Preamplifiers

Input signal connector

Shielding of front-end
LAr-TPC DAQ architecture

- T600 event builder architecture based on network characterized by 2 level switching layers.

- Event Builder: 4 independent DAQ hosts and Disk Arrays (> 30 TB) as short term storage (~400K full drift events).

- Segmentation / parallelization of data stream (e.g. 12 readout units per builder unit) allow reaching a building rate > 1 Hz on the whole T600, largely adequate to match trigger rate @ LNGS (from cosmic rays).
The presence of electron trapping polar impurities attenuates the electron signal as 
\[ \exp\left(-\frac{t_d}{\tau_{\text{ele}}}\right) \]
\[ \tau_{\text{ele}} \sim 300 \mu s / \text{ppb} \ (O_2 \text{ equivalent}). \]

Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O$_2$, H$_2$O, CO$_2$.

Recirculation/purification (100 Nm$^3$/h) of the gas phase (~40 Nm$^3$) to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) into the bulk liquid.

Recirculation/purification (4 m$^3$/h) of the bulk liquid volume (~550 m$^3$) to efficiently reduce the initial impurities concentration (can be switched on/off).
Lar filling

Filling procedure with ultra pure (ppt) LAr:

- Use ultra high vacuum standards for detector components design, construction, cleaning and assembly;
- Removal of air and outgassing of surfaces by evacuating the argon container volume to the molecular vacuum level ($\approx 10^{-5}$ mbar);
- Fast cooling (to minimize out-gassing) and filling with ultra-purified LAr;
- Recirculation/purification of the gas phase to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) in the bulk liquid;
- Recirculation/purification of the bulk liquid volume to further reduce the impurities concentration.
Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

\[
dN/dt = -N/\tau_R + k + k_I \exp(-t/\tau_I)
\]

\(\tau_{ele} \text{[ms]} = 0.3 / N[\text{ppb O}_2 \text{ equivalent}]\)

\(\tau_R: \text{ recirculation time for a full detector volume}\)
\(kI \text{ and } \tau_I: \text{ related to the total degassing internal rate}\)
\(k: \text{ related to the external leaks}\)

\(\tau_R: 2 \text{ m}^3/\text{h corresponding to } \approx 6 \text{ day cycle time}\)

**LAr continuous recirculation mandatory to maintain purity**
ICARUS T600 physics potential

● T600 is a major milestone towards the realization of a much more massive multikton LAr detector, but it offers also some interesting physics in itself. The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π⁰ separation allow “to see” events in a new way.

● The detector is collecting “bubble chamber like” CNGS events: for 10²⁰ pot
  ➢ CC event expected ≈ 1300 ev/y
  ➢ NC event expected ≈ 400 ev/y
  ➢ Muons from upstream GS rock ≈ 5500 ev/y (≈ 3700 on TPC front face)
  ➢ Intrinsic beam νₑ CC ≈ 12 ev/y
  ➢ νᵢ => νₜ detecting τ decay with kinematical criteria (~1.3 τ->e ev/y)
  ➢ νᵢ => νₑ ( ₁₃θ ) from e-like CC events excess at E < 20 GeV (~2.2 CC/y)
  ➢ Search for sterile neutrinos in LSND parameter space, with e-like CC events excess at 30 GeV > E > 10 GeV.

● The T600 is also collecting simultaneously “self triggered” events:
  ➢ ≈ 100 ev/year of atmospheric ν CC interactions.
  ➢ Proton decay with 3x10³² nucleons, zero bckg. in some of the channels.
ICARUS T600 trigger system

● CNGS:
  ➢ CNGS “Early Warning” signal sent 80 ms before the SPS p extraction: allows opening a 60 ms wide gate around neutrino arrival time at LNGS.
  ➢ PMT sum signal for each chamber in coincidence with the beam gate.
  ➢ 2.40 ms offset value in agreement with 2.44 ms $\nu$ tof (40 $\mu$s fiber transit time from external lab to Hall B)
  ➢ Spill duration reproduced (10.5$\mu$s), 1 mHz event rate, $\approx$ 80 events/day

● Cosmic Rays:
  ➢ PMT sum signal: coincidence of two adjacent chambers (50% cathode transparency)
  ➢ Globally 36 mHz trigger rate achieved: $\sim$130 cosmic events/h

● Local trigger based on deposited charge (SuperDaedalus):
  ➢ on-line hit-finding/zero-skipping algorithm implemented in FPGA’s, used to improve trigger efficiency at low energy (below 500 MeV)
The abundant prompt scintillation light in LAr is exploited as global trigger and to determine the event depth along the drift path.

- VUV (128 nm) light detection

- Specially developed PMT's directly immersed in LAr
  - Bialkali photocathode + Platinum underlayer to reduce cathode resistivity at low temperature
    - ETL 9357FLA 8” PMs with > 15% peak Q.E (420 nm) at 87 K

- Borosilicate glass window with wavelength shifter coating
  - Thin layer of Tetra Phenyl-Butadiene >100% conversion 128 nm -> 420 nm (blue region)

- Large detection coverage

TPB as WLS: Lally et al., NIM-B 117 (1996) 421
ICARUS T600 Light PMT DAQ

- Custom low-noise integrating preamp \((RC=10\ \mu\text{s})\) for each PMT + external active signal adder to exploit the light slow component \((1.6\ \mu\text{s})\) for triggering purposes (on dedicated FPGA trigger box).

- Fast \((6\text{ns})\) light component picked up/exploited for prompt signal generation for \(\nu\) TOF measurement & PMT monitoring

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Low noise preamp. and active adders

Fast component pickup

Independent DAQ system, based on “2-channel, 8-bit, 1-GHz ACQIRIS AC240” digitizer boards, triggered by the ICARUS-CNGS trigger.
Double Rebinning sliding window algorithm implemented in a new SuperDaedalus chip mounted on T600 DAQ for on-line hit finding on TPC wires [Jinst 5:P12006 (2010)].

2nd step of the algorithm: Majority trigger

\[ Q_8(t) = \frac{1}{8} \sum_{i=0}^{8} Q(t-i) \]

\[ Q_{128}(t) = \frac{1}{128} \sum_{i=0}^{128} Q(t-i) \]

\[ S(t) = Q_{8}(t) - Q_{128}(t) \]

Peak stretching ranging in 25÷125 μs to guarantee high efficiency for inclined tracks

Peak signal generated when \( S(t) \) over threshold

A trigger is fired when peak’s majority is satisfied
Triggering with SuperDaedalus

Low events detected by SuperDaedalus trigger and not by PMT trigger.

Run 10354 Ev 85

Short muons tracks

Run 10356 Ev 474

~2 MeV isolated electron

Collection view

Collection view

Possible use also for efficient data reduction
(DAQ architecture already designed to include this feature)

Full drift image

SDaedalus “tiles” selection

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ICARUS T600: progress on data analysis

- The analysis of CNGS neutrino events is ongoing. First results available.
- First step on cosmic-ray analysis: automatic reconstruction of deposited energy from c-muons in agreement with expectations
- Optimization of analysis tools in term of performance, calibrations and event reconstruction:
  - Progresses in 3D reconstruction, leading to better performance especially for horizontal tracks
  - Momentum measurement by m.s. for escaping muons, under refinement
  - Progresses in the Particle Identification Algorithm
  - Progresses in automatic reconstruction: vertex finding, clustering, track finding
  - Developments on tools for calorimetric reconstruction
- An extremely powerful detector observing very complex, high energy, high multiplicity events
- Lot of work has been done, much more is needed
3D reconstruction and particle identification

- 3D reconstruction from 2D based on Polygonal Line Algorithm (PLA), linking hits in different views according to:
  - drift sampling;
  - sequence of hits.

- Particle identification based on:
  - distance between nearby 3D hits: $dx$
  - 3D hits and charge deposition: $dE/dx$

- Energy reconstructed, quenching included

<table>
<thead>
<tr>
<th>pid</th>
<th>p</th>
<th>K</th>
<th>π</th>
<th>μ</th>
<th>efficiency [%]</th>
<th>purity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>481</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>99.2</td>
<td>98.0</td>
</tr>
<tr>
<td>K</td>
<td>10</td>
<td>380</td>
<td>0</td>
<td>0</td>
<td>97.4</td>
<td>99.0</td>
</tr>
<tr>
<td>π</td>
<td>0</td>
<td>0</td>
<td>196</td>
<td>40</td>
<td>83.1</td>
<td>98.5</td>
</tr>
<tr>
<td>μ</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>216</td>
<td>98.6</td>
<td>84.4</td>
</tr>
</tbody>
</table>

High identification efficiency for $p$, $K$, $\pi$, $\mu$
Calibration with stopping particles: examples

**Color bands: MC**
- Blue: protons
- Red: kaons
- Green: pions
- Violet: muons
- Dots: hits from real tracks

- Deposited $dE/dx$ vs residual range
- No quenching correction
- Black dots: not consistent with any pattern, most probably protons interacting at very low energy with emission of neutrons and photons

Methods for identification of non-stopping particles are under development (including quenching correction)
**3D reconstruction (example of stopping $\mu$)**

**New:** Overall 3D Polygonal Line Algorithm fit optimized to all available hits in the 2D wire planes and all identified 3D ref. points (vertices, delta rays). 2D hit-to-hit associations no longer needed -> missing parts in a single view and horizontal tracks fully accepted.

$\mu \ [AB] \rightarrow e \ [BC]$  

T300 real event  
$Te=35.5$ MeV  
$Range=13.4\text{cm}$

Important step forward for T600 and for future LAr detectors
6 protons, 1 pion decays at rest

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_{\text{dep}}$ [MeV]</th>
<th>range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(p)</td>
<td>185±16</td>
<td>15</td>
</tr>
<tr>
<td>5(p)</td>
<td>192±16</td>
<td>20</td>
</tr>
<tr>
<td>7(p)</td>
<td>142±12</td>
<td>17</td>
</tr>
<tr>
<td>8(π)</td>
<td>94±8</td>
<td>12</td>
</tr>
<tr>
<td>9(p)</td>
<td>26±2</td>
<td>4</td>
</tr>
<tr>
<td>10(p)</td>
<td>141±12</td>
<td>23</td>
</tr>
<tr>
<td>11(p)</td>
<td>123±10</td>
<td>6</td>
</tr>
</tbody>
</table>
Example of data: kaon decay in a CNGS event

- Kaon track
- Muon track

Corresponding PID patterns:

- Decay vertices
  - Kaon: $\sim 90\text{cm, 325MeV}$
  - Muon: $\sim 54\text{cm, 147MeV}$
  - Electron: $\sim 13\text{cm, 27MeV}$

Collection view
\( \pi^0 \) reconstruction

\( \pi^0 \) showers identified by:

- 2\( \gamma \) conversion separated from primary vertex
- Reconstruction of \( \gamma \gamma \) invariant mass
- Ionization in the first segment of showers

\( M_{\gamma\gamma} = 133.8 \pm 4.4\text{(stat)} \pm 4 \text{ (syst)} \text{ MeV}/c^2 \)

\( \pi^0 \) 44°

\( \pi^0 \) 65°

Initial ionizations:
- 5.1, 6.1, 3.1 and 4.4 MeV/cm

Wire coordinate (~3 m)

Conversion distances:
- 71.2 cm, 13.7 cm, 41.8 cm, 17.4 cm

From CNGS Real Data

dE/dx of the initial part of low E showers

dE/dx from a single long stopping muon (p=1.8 GeV/c)

Most Probable dE/dx in agreement with expectation

Single mip due to Compton electrons (low E \( \pi^0 \))
Muon momentum by multiple scattering.

- Key tool to measure momentum of non-contained μ's: essential for atmospheric / CNGS ν's.

- Kalman fit of the segmented μ track (segment length $L_{seg}$).

- Momentum $p$ extracted from deflection angle $\theta$, $\chi^2$ of fit.

- Method under development and validation on stopping μ's and extended to higher energy.

- $\Delta p/p$ depends mainly on track length: for CNGS $\Delta p/p < 20\%$ expected on average.
Muon momentum by multiple scattering.

For MS measurement, a “preparation” of the track is mandatory:

- Ordering of the hits, rejection of delta rays and outliers

Encouraging results for stopping muons and long CNGS tracks (>2.5m)
Present expected overall resolution ~ 30% in 10 - 30 GeV range, refinements still ongoing
Primary vertex: very long $\mu$ (1), e.m. Cascade (2), p (3).

Secondary vertex:
Longest track (5) is $\mu$ coming from stopping k (6), $\mu$ decay observed.

$p_\mu$ by multiple scattering (~11 GeV)

Conversion distances
6.9 cm, 2.3 cm

$M^* = 125\pm15$ MeV/c$^2$

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_{\text{dep}}$ [MeV]</th>
<th>$\cos x$</th>
<th>$\cos y$</th>
<th>$\cos z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($\mu$)</td>
<td>2702</td>
<td>0.069</td>
<td>-0.040</td>
<td>-0.997</td>
</tr>
<tr>
<td>2</td>
<td>521</td>
<td>0.054</td>
<td>-0.420</td>
<td>-0.906</td>
</tr>
<tr>
<td>3 ($\pi$)</td>
<td>514</td>
<td>-0.001</td>
<td>0.137</td>
<td>-0.991</td>
</tr>
<tr>
<td>Sec. vtx.</td>
<td>797</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>77</td>
<td>0.009</td>
<td>-0.649</td>
<td>0.761</td>
</tr>
<tr>
<td>5 ($\mu$)</td>
<td>314</td>
<td>0.000</td>
<td>-0.239</td>
<td>-0.971</td>
</tr>
<tr>
<td>6 (K)</td>
<td>87</td>
<td>0.414</td>
<td>0.793</td>
<td>-0.446</td>
</tr>
<tr>
<td>7</td>
<td>36</td>
<td>-0.613</td>
<td>0.150</td>
<td>-0.776</td>
</tr>
<tr>
<td>8</td>
<td>283</td>
<td>4.5 GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A $\nu_e$CC candidate from 2010 run. Total energy is 45 GeV with a single energetic 37 GeV e.m. shower at the vertex with a longitudinal profile peaking at the expected position (~88 cm).
Comparison of the predicted (full MC) and detected deposited energy spectrum from NC and CC events on 2010 statistics and a subset of the 2011 statistics.

On-going: separation of e.m. from hadronic components for better compensation corrections.
Atmospheric $\nu$ candidate

- Total visible energy: 887 MeV
- Out-of-time wrt CNGS spill, 350° angle w.r.t. beam direction.

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<thead>
<tr>
<th>Track</th>
<th>$E_k$ [MeV]</th>
<th>Range [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($\pi$, decays in flight)</td>
<td>136.1</td>
<td>55.77</td>
</tr>
<tr>
<td>2 ($\pi$)</td>
<td>26</td>
<td>3.3</td>
</tr>
<tr>
<td>2a ($\mu$)</td>
<td>79.1</td>
<td>17.8</td>
</tr>
<tr>
<td>2b (e)</td>
<td>24.1</td>
<td>10.4</td>
</tr>
<tr>
<td>3 ($\mu$)</td>
<td>231.6</td>
<td>99.1</td>
</tr>
<tr>
<td>4 (p)</td>
<td>168</td>
<td>19.2</td>
</tr>
<tr>
<td>5 (p)</td>
<td>152</td>
<td>16.3</td>
</tr>
<tr>
<td>6 (?) (merged with vtx)</td>
<td>168</td>
<td>2.9</td>
</tr>
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Very small event
Summary: LAr-TPC performance

Tracking device
- Precise 3D event topology ~1 mm³
- $\mu$ momentum measurement via multiple scattering $\Delta p/p \sim 15$-20%

Measurement of local energy deposition
- $e/\gamma$ separation (2% $X_0$ sampling)
- Particle ID by means of $dE/dx$ vs range

Total energy reconstruction by charge integration
- Full sampling, homogeneous calorimeter with excellent accuracy

Reconstructed $\nu_\mu$ CC event from CNGS beam

**RESOLUTIONS**

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})}+2\%$
Electromagnetic showers: $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(\text{GeV})}$
Conclusions

- Icarus T600 is the first large LAr TPC operated underground.
- The T600 is acquiring data without interruption since mid-2010 @ LNGS with CNGS beam, searching for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations as well as for atmospheric $\nu$'s and proton decay.
- Its unique imaging capability, spatial/calorimetric resolutions, and $e/\pi^0$ separation allow to reconstruct/identify events in a new way, w.r.t. previous/current experiments: a major milestone towards a much more massive LAr detector.
- High detection efficiency reached for CNGS events. Quality of data as expected.
- Data analysis in progress, results expected on:
  - Search for $\nu_\mu \rightarrow \nu_e$ oscillations and LNSD effect
  - Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Contributions to the “superluminal” neutrino problem
- After CNGS stop (Dec 2012), data taking at LNGS will continue until mid 2013.
- T600 transfer to CERN for sterile neutrino search on SBL beam is foreseen.