The ICARUS T600 detector at LNGS underground laboratory

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on behalf of the ICARUS Collaboration

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A powerful detection technique

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

Electrons from ionizing track are drifted in LAr by $E_{\text{drift}}$. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.

**Key feature**: LAr purity from electro-negative molecules ($O_2$, $H_2O$, $CO_2$). Target: 0.1 ppb $O_2$ equivalent $= 3$ ms lifetime (4.5 m drift @ $E_{\text{drift}} = 500$ V/cm).
ICARUS Milestones

2. 3 ton prototype
3. 50 litres prototype 1.4 m drift chamber
4. 10 m³ industrial prototype
5. Laboratory work
6. 24 cm drift wires chamber


Pavia

2001: First T600 module

Cooperation with industry and several companies

CERN

2010 - … : Data taking with CNGS beam

LNGS Hall-B

2010 - … : Data taking with CNGS beam

TIPP2011 - N. Canci
LAr-TPC performance

- Tracking device:
  - precise event topology ($s_{x,y} \sim 1\text{mm}, s_z \sim 0.4\text{mm}$)
  - $\mu$ momentum measurement via multiple scattering: $\Delta p/p \sim 10-15\%$ depending on track length and $p$
  - Total energy reconstruction by charge integration

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

- Good $e/\pi^0$ separation ($10^{-3}$) by means of $dE/dx$ in the first part of the track after the vertex; $\pi^0$ mass measurement

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): $\sigma(E)/E \approx 30\% / \sqrt{E(\text{GeV})}$
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
  - $HV = -75 \text{ kV}$  $E = 0.5 \text{ kV/cm}$
  - $v_{\text{drift}} = 1.55 \text{ mm/µs}$

- **4 wire chambers**:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - $\approx 54000$ wires, 3 mm pitch, 3 mm plane spacing

- **PMT for scintillation light**:
  - $(20+54) \text{ PMTs}, \ 8'' \ Ø$
  - VUV sensitive (128nm) with wave shifter (TPB)
ICARUS T600 in LNGS Hall B

30 m³ LAr Vessel

30 m³ LN₂ Vessel

N₂ Phase separator

N₂ liquefiers: 12 units, 48 kW total cryo-power
Continuous waveform Recording

ICARUS front-end Electronics

Liquid argon | Gas
--- | ---
Sense wires (4-9m, 20pF/m) | Twisted pair cables (~5m, 50pF/m)

Decoupling Boards (32 ch.)

Front-end amplifiers (32/board): 1500 e.n.c

10bit FADC 400ns sampling 1mV/ADC (~1000e-/ADC matches el. Noise)

H.V. (±300 V)

Multi-event circular buffer (8x1ms)

VME board (18/crate) 4 Multiplexers (400ns x 8ch.)

To storage
The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{\text{ele}})$.

$\tau_{\text{ele}} \sim 300 \mu s / \text{ppb} (O_2 \text{ equivalent})$.

Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: $O_2$, $H_2O$, $CO_2$.

Recirculation/purification (100 Nm$^3$/h) of the gas phase ($\sim$40 Nm$^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 ($\sim$550 m$^3$) to efficiently reduce the initial impurities concentration (can be switched on/off).
LAr purity measurement with muon crossing tracks

Charge attenuation along track allows event-by-event measurement of LAr purity.

T = 0 estimated by induction of PMT signal on Collection view.

Wire 3695

Pulse height for 3 mm m.i.p.
~ 15 ADC # (15000 electrons)

Noise r.m.s.
~ 1.5 ADC # (1500 electrons)
LAr purity time evolution

Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

\[ \frac{dN}{dt} = -\frac{N}{\tau_R} + k_I + k_D \exp\left(-\frac{t}{\tau_D}\right) \]

- \( \tau_R \): recirculation time for a full detector volume
- \( k_D \) and \( \tau_D \): related to the total degassing internal rate
- \( k_I \): totally impurity leak rate and degassing rate

\( \tau_R \): 2 m³/h per half module corresponding to \( \approx 6 \) day cycle time

\( \tau_{ele} \) [ms] = \( \frac{0.3}{N[\text{ppb } \text{O}_2 \text{ equivalent}]} \)
ICARUS T600: major milestone towards realization of large scale LAr detector. Interesting physics in itself: unique imaging capability, spatial/calorimetric resolutions and $e/\pi^0$ separation → events “seen in a new Bubble chamber like” way.

CNGS $\nu$ events collection (beam intensity $4.5 \times 10^{19}$ pot/year, $E_\nu \sim 17.4$ GeV):
- 1200 $\nu_\mu$ CC event/year;
- $\sim 8$ $\nu_e$ CC event/year;
- observation of $\nu_\tau$ events in the electron channel, using kinematical criteria;
- search for sterile $\nu$ in LSND parameter space (deep inelastic $\nu_e$ CC events excess).

“Self triggered” events collection:
- $\sim 80$ events/y of unbiased atmospheric $\nu$ CC;
- zero background proton decay with $3 \times 10^{32}$ nucleons for “exotic” channels.
Preliminary results of first CNGS 2010 run

- ICARUS fully operational for CNGS events recording in Oct. 1\textsuperscript{st} - Nov. 22\textsuperscript{nd}.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.

Oct. 1\textsuperscript{st} ÷ Nov. 22\textsuperscript{nd}: 8 \cdot 10^{18} (5.8 \cdot 10^{18}) pot delivered (collected). Detector lifetime up to 90% since Nov. 1\textsuperscript{st}.

Number of collected interactions compared with number of interactions predicted ((2.6 v CC + 0.86 v NC) 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume (424 t) and DAQ dead-time.

5.3 \cdot 10^{18} pot = 91 % out of whole sample

<table>
<thead>
<tr>
<th>Event type</th>
<th>Collected</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν\textsubscript{μ} CC</td>
<td>108</td>
<td>115</td>
</tr>
<tr>
<td>νNC</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>νXC *</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>150</td>
<td>152</td>
</tr>
</tbody>
</table>

- Events at edges, with μ track too short to be visually recognized: further analysis needed.

On overall statistics in agreement with expectations.
CNGS neutrino interactions in ICARUS T600

Collection view

Wire coordinate (8 m)

Drift time coordinate (1.4 m)

CNGS $\nu$ beam direction

$\nu_{\mu}$ CC
Low energy CNGS neutrino interaction

Electron lifetime and quenching accounted for

Collection views (not to scale!)

Evis ~ 9 GeV

CNGS beam

Left wire chamber

0.5 m

Electron drift (1.5 m)

Cathode (18 m)

Right wire chamber

Electron drift (1.5 m)

1.8 m
CNGS NC interaction

Wire coordinate (2.2 m)

Drift t coordinate (1.5 m)

CNGS ν beam direction
3D reconstruction and (nn) particle identification

- Complement of 2D reconstruction based on Polygonal Line Algorithm (PLA).
  
  http://www.iro.umontreal.ca/~kegl/research/pcurves/

- 3D reconstruction: linking hit projections between views according to
  - drift sampling;
  - sequence of hits.

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

- Classify single \(i^{th}\) point on the track
  \[ p_i : [E_k, dE/dx] \rightarrow nn_i : [P(p), P(K), P(p), P(\mu)] \]

- Average \(M\) output vectors for the points
  \[ NN = S(nn_i)/M \]

- Identify track as particle corresponding to \(\text{max}(NN)\)
  very high identification efficiency for \(p, K, \pi^+, \mu\)

- Energy reconstructed including quenching in simulation
Primary vertex (A)
very long \( \mu \) (1),
e.m. cascade(2),
pion (3).

Secondary vertex (B)
The longest track (5) is a \( \mu \) coming from stopping k (6).
- \( \mu \) decay is observed.

\[ p_\mu = 10.5 \pm 1.1 \text{ GeV/c by multiple scattering} \]

\[ E_{\text{dep}} = [\text{MeV}] \]

<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>2701.97</td>
<td>0.069</td>
<td>-0.040</td>
<td>-0.997</td>
</tr>
<tr>
<td>2 (( \pi^0 ))</td>
<td>520.82</td>
<td>0.054</td>
<td>-0.420</td>
<td>-0.906</td>
</tr>
<tr>
<td>3 (( \pi ))</td>
<td>514.04</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>76.99</td>
<td>0.009</td>
<td>-0.649</td>
<td>0.761</td>
</tr>
<tr>
<td>5 (( \mu ))</td>
<td>313.9</td>
<td>0.009</td>
<td>-0.649</td>
<td>0.761</td>
</tr>
<tr>
<td>6 (K)</td>
<td>86.98</td>
<td>0.000</td>
<td>-0.239</td>
<td>-0.971</td>
</tr>
<tr>
<td>7</td>
<td>35.87</td>
<td>0.414</td>
<td>0.793</td>
<td>0.446</td>
</tr>
<tr>
<td>8</td>
<td>283.28</td>
<td>-0.613</td>
<td>0.150</td>
<td>-0.776</td>
</tr>
</tbody>
</table>

**LAr-TPC: powerful technique. Run 9927 Event 572**

**Close-up of two e.m. showers**

**Primary vertex (A)**
very long \( \mu \) (1),
e.m. cascade(2),
pion (3).

**Secondary vertex (B)**
The longest track (5) is a \( \mu \) coming from stopping k (6).
- \( \mu \) decay is observed.

**Track**
- 1 (\( \mu \))
- 2 (\( \pi^0 \))
- 3 (\( \pi \))
- Sec. vtx.
- 4
- 5 (\( \mu \))
- 6 (K)
- 7
- 8

**Conversion distances**
6.9 cm, 2.3 cm

**Total visible energy** 4.5 GeV

**\( p_\mu \) = 10.5 \pm 1.1 \text{ GeV/c by multiple scattering} \)**

**\( M_{\gamma\gamma}^* = 125 \pm 15 \text{ MeV/c}^2 \)**

**Run 9927 Event 572**

**Total visible energy** 4.5 GeV

**\( p_\mu \) = 10.5 \pm 1.1 \text{ GeV/c by multiple scattering} \)**
Atmospheric ν candidate

- Total visible energy: 887 MeV (including quenching and e⁻ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.
2011-2012 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: expected $10^{20}$ pot.
- For $1.1 \times 10^{20}$ pot: 3000 beam related $\nu_\mu$ CC events expected in ICARUS-T600.

- $\tau \rightarrow e\nu\nu$ events characterized by momentum unbalance (because of $2\nu$ emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts and efficiency ~ 50%, allowing to detect 1-2 $\nu_\tau$ CNGS events expected in ICARUS T600 in next 2 years.

- At the effective neutrino energy of 20 GeV and $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$, $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\%$.
- 17 raw CNGS beam-related $\nu_\tau$ CC events expected.
- $P(\tau \rightarrow e\nu\nu) = 18\% \Rightarrow 3$ electron deep inelastic events with visible energy < 20 GeV.
Conclusions

Cryogenic noble liquids and Argon in particular have recently regained a strong interest in the scientific community.

The ICARUS experiment at the Gran Sasso Laboratory is so far the most important milestone for this technology and acts as a full-scale test-bed located in a difficult underground environment.

- The successful assembly and operation of the ICARUS-T600 LAr-TPC demonstrate that the technology is mature.

- The wide physics potentials offered by high granularity imaging and extremely high resolution will be addressed already with the T600 detector:
  - Underground physics (proton decay, atmospheric $\nu$, supernova, ...)
  - Long-baseline neutrino oscillation physics

- The T600 is presently taking data, recording cosmic and CNGS neutrino events in stable conditions since October 2010. Data analysis is on-going.

- The detector is ready for the 2011-2012 CNGS high intensity exposure.
Sterile neutrino search with ICARUS T600

- Sensitivity region, in terms of standard deviations, for 3000 raw CNGS muon neutrino events.
- The potential signal is above the background generated by the intrinsic $\nu_e$ beam contamination, in the deep inelastic interval 10-30 GeV.
- Largely complementary to the Fermi-lab program in terms of energy and baseline.

$\nu_\mu \rightarrow \nu_e$ appearance search in T600 in LNSD parameter space
CNGS run during 2010

- ICARUS fully operational for CNGS events recording in Oct. 1\textsuperscript{st} – Nov. 22\textsuperscript{nd}.
- At every CNGS cycle 2 spills lasting 10.5 µs each, 50 ms apart; ppp = 2.1 \times 10^{13}.
- CNGS “Early Warning” signal sent 80 ms before the proton spill extraction, containing information on the time foreseen for the next extraction.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 µs wide beam gate.

Oct. 1\textsuperscript{st} – Nov. 22\textsuperscript{nd}: 8 \times 10^{18} (5.8 \times 10^{18}) pot delivered (collected). Detector lifetime up to 90% since Nov. 1\textsuperscript{st}. 
A CNGS $\nu_\mu$ interaction with time coincidence

Wire coordinate (~4 m)

Collection view

Drift time coordinate (1.4 m)

Induction 1 (Front view)

CNGS $\nu$ beam direction

CNGS abs. extr. time: 2010-06-20 23:41:10:935

T600 LNGS mean time: 2010-06-20 23:41:11