ICARUS and Status of Liquid Argon technology

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On behalf of the ICARUS Collaboration
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The detection technique

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

- Continuously sensitive, self triggering.
- High granularity (spatial resolution ≈ 1 mm$^3$)
- Excellent calorimetric properties.

Electrons from ionizing tracks are drifted in LAr by a uniform electric field. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by a collection wire plane.
The ICARUS T600 detector

- Two identical T300 modules (two chambers per module)
  - Liquid Ar active mass: $\approx 476$ t
  - $(17.9 \times 3.1 \times 1.5$ for each TPC) m$^3$
  - drift length = 1.5 m
  - $E_{\text{drift}} = 500$ V/cm; $v_{\text{drift}} = 1.589$ mm/$\mu$s

- Three readout wire planes per chamber, at 0, $\pm 60^\circ$, 3 mm plane spacing
  - $\approx 53.000$ wires, 3 mm pitch
  - Two induction planes, one collection

- PMTs for scintillation light (128 nm)
  - 20+54 PMTs, 8” $\varnothing$
  - wave shifter (TPB)

Key feature: LAr purity form electro-negative molecules ($O_2, H_2O, CO_2$). Target: 0.1 ppb $O_2$ equivalent = 3 ms lifetime (4.5 m drift @ 500 V/cm).
Electronegative impurities can attenuate $e^-$ signal: high purity is crucial!

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

$$\tau_{ele} [ms] = 0.3 / N[ppb O_2 \text{ equivalent}]$$

**Present value < 0.05 ppb (6 ms lifetime)**
CNGS trigger

- At every CNGS cycle protons are extracted in 2 spills lasting 10.5 µs each, 50 ms apart. CNGS “Early Warning” signal sent 80 ms before the proton spill extraction, containing information on the time foreseen for the next extraction.
- Trigger: PMT analog sum signal for each chamber with low threshold discrimination at 100 phe, within 60 µs wide beam gate.
- 80 events per day are recorded with a trigger rate of about 1 mHz.

Offset value (2.40 ms) in agreement with ν t.o.f. (2.44 ms) in view of 40 µs fiber transit time from external LNGS labs absolute clock to Hall B (8km).
First CNGS $\nu$ interaction in ICARUS T600

Collection view

Wire coordinate (8 m)

CNGS $\nu$ beam direction

Drift time coordinate (1.4 m)
Another CNGS CC $\nu$ interaction

Wire coordinate (8 m)

CNGS $\nu$ beam direction

Drift t coordinate (1.5 m)
CNGS CC $\nu$ interaction with signal in both TPCs

$E_{\text{vis}} \approx 9 \text{ GeV}$
Predicted number of collected interactions in the rock: $7.8 \cdot 10^{-17}$/pot
CNGS NC $\nu$ interaction

Wire coordinate (2.4 m)

CNGS $\nu$ beam direction

Drift t coordinate (1.5 m)
CNGS CC $\nu$ interaction with $\pi^0$ production

Total deposited energy $\approx 1\text{ GeV}$
ICARUS fully operational for CNGS events recording since October, 1st.

- $5.9 \cdot 10^{18}$ pot collected (75% live time).
- Number of $\nu$ interaction within expectations.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Collected</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>114</td>
<td>129</td>
</tr>
<tr>
<td>$\nu$ NC</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\nu$ XC (further analysis needed)</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>167</td>
<td>171</td>
</tr>
</tbody>
</table>
ICARUS T600 reconstruction performances

CASCADeS:
- The total energy of cascades is measured by charge integration with recombination correction.

> Very good e/\(\pi^0\) separation by means of dE/dx in the first part of the cascade.

NC \(\pi^0\) background rejected at 0.1% level while keeping 90% of \(\nu_e\) CC

ENERGY 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)}

TRACKS:
- Momentum of high energy particles is measured via multiple scattering:
  \(\Delta p/p \approx 10-15\%\) depending on track length and \(p\).
- Stopping particles energy is measured by charge integration.
- Stopping particle identification by means of dE/dx vs E.

Requires good spatial reconstruction
Full reconstruction of a typical CNGS CC $\nu_\mu$ event

Total visible energy
4.5 GeV

$p_\mu = 10.5 \pm 1.1$ GeV/c by multiple scattering

close-up of two e.m. showers

Primary vertex (A):
(1) long muon (uncontained)
(2) e.m. Cascades
(3) pion

Secondary vertex (B):
the longest track (5) is a $\mu$ coming from stopping kaon (6). The $\mu$ decay is also observed

Total transverse momentum is consistent with Fermi distr.

$P_T$ unbalance $\sim 250$ MeV

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

Conversion distances 6.9 cm, 2.3 cm
Low energy $\nu$ interaction

Total visible energy: 887 MeV (including quenching and $e^-$ lifetime corrections).
### Atmospheric neutrino candidate

- **Total deposited energy:** 887 MeV
- **Total reconstructed momentum:** 929 MeV/c at about 35° away from the CNGS beam direction
- **Outside CNGS spill gate**

**Track**

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

**Diagram**

- Track 1 (prob. $\pi$, decays in flight)
- Track 2 ($\pi$)
- Track 2a ($\mu$)
- Track 2b (e)
- Track 3 ($\mu$)
- Track 4 (p)
- Track 5 (p)
- Track 6 (?) (merged with vtx)

**3D View**

- 1
- 2a + 2b
- 3
- 4
- 5

- **Z**
- **Y**
- **X**
Preliminary results of CNGS 2010 CC ν interactions

Measurement of muon momentum from multiple scattering

Calorimetric measurement of the deposited energy
Reconstruction of muons from $\nu$ interaction in the rock

Direction of muons w.r.t. the vertical:

$<\theta> = 86.32 \pm 0.31$

Muon azimuth:

$<\phi> = -0.10 \pm 0.22$
- Beam restarted from March, 19th.
- Detector live time above 92% due to more stable run conditions
- $3.46 \cdot 10^{19} \ (3.74 \cdot 10^{19})$ pot delivered (collected) up to August, 28th.
- Total deposited energy 45 GeV.
- Single high energy EM shower (37 GeV) measured by charge integration, partially overlapped to hadronic jet.
ICARUS T600 physics potential (2011-2012 CNGS run)

- 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.

- 2011-2012 run with dedicated SPS periods @ high intensity (10^{20} pot, E_\nu \approx 17.4 \text{ GeV}).

- For 1.1 \cdot 10^{20} pot: 3000 beam related \nu_\mu CC events expected in ICARUS T600.
  - 7 \nu_\mu CC intrinsic beam associated events with E_{vis} < 20 \text{ GeV} → \text{BACKGROUND};
  - 17 \nu_\tau raw CC events assuming P(\nu_\mu \rightarrow \nu_\tau) = 1.4\% (\Delta m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2 , E_\nu = 20 \text{ GeV});
  - P(\tau \rightarrow e\nu\nu) = 18\% → 3 electron deep inelastic events with visible energy < 20 \text{ GeV} → \text{SIGNAL}:
    - \tau \rightarrow e\nu\nu events are characterized by momentum unbalance (2\nu emission) and relatively low electron momentum.
    - Selection criteria suggest a sufficiently clean separation with kinematic cuts and 50\% efficiency, opening the possibility to identify 1-2 \nu_\tau CNGS events in the next 2 years, only in this gold channel.

- search for sterile \nu in LSND parameter space (deep inelastic \nu_\mu CC events excess).

- \text{Self triggered} events collection:
  - \approx 80 events/year of unbiased atmospheric \nu CC;
  - zero background proton decay with 3 \times 10^{32} nucleons for \text{exotic} channels.
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.

\[\nu_\mu \rightarrow \nu_e \text{ appearance search in T600 in LNSD parameter space}\]
ICARUS T600 @ LNGS is taking data with the CNGS beam in stable conditions since October 2010.

The successful assembly and operation of ICARUS T600 is the experimental proof that this technique is suitable for large scale experiments.

The unique imaging capability of ICARUS and its spatial and calorimetric resolutions allow to reconstruct and identify events in a new way w.r.t. previous and current experiments.

The 2011-2012 run with CNGS $\nu_\mu$ beam will allow to possibly detect few $\nu_\tau$ appearance events. Interesting perspective also for atmospheric neutrinos, sterile neutrinos and proton decay.

*The ICARUS experiment at the Gran Sasso Laboratory is so far a major milestone towards the realization of much more massive LAr detectors.*
Thank you!