ICARUS and Status of Liquid Argon technology

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On behalf of the ICARUS Collaboration
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: ≈ 476 t
  - $(17.9 \times 3.1 \times 1.5$ for each TPC) $m^3$
  - drift length = 1.5 m
  - $E_{\text{drift}} = 500 \text{ V/cm}; v_{\text{drift}} = 1.589 \text{ mm/μs}$

- Three readout wire planes per chamber, at $0, \pm 60^\circ, 3 \text{ mm plane spacing}$
  - ≈ 53,000 wires, 3 mm pitch
  - Two induction planes, one collection

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

Key feature: LAr purity form electro-negative molecules ($O_2, H_2O, C_2O_2$).
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.

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

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

\[ \frac{dN}{dt} = -N/\tau_R + k + k_1 \exp \left( -t/\tau_1 \right) \]

\( \tau_R \): recirculation time for a full detector volume
\( k_i \) and \( \tau_i \): related to the total degassing internal rate
\( k \): related to the external leaks
\( \tau_R \): 2 m³/h corresponding to ≈ 6 day cycle time
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 ν interaction in ICARUS T600

Collection view

Wire coordinate (8 m)

CNGS ν beam direction

Drift time coordinate (1.4 m)
Another CNGS CC ν interaction

Wire coordinate (8 m)

CNGS ν beam direction

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

Wire coordinate 1.8 m

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

Drift t coordinate (1.5 m)

Wire coordinate (2.4 m)

CNGS ν beam direction
CNGS CC $\nu$ interaction with $\pi^0$ production

Collection view

Wire coordinate ($\sim 3$ m)

CNGS $\nu$ beam direction

Induction 1

Total deposited energy $\approx 1$ GeV

Induction 2 view
ICARUS fully operational for CNGS events recording since October, 1st.

5.9 \cdot 10^{18} \text{ 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

CASCADAS:

- 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) $\sigma(E)/E \approx 3%/\sqrt{E\text{(GeV)}}$

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
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.

\( M^{\gamma\gamma} = 125 \pm 15 \) MeV/c²

\( P_T \) unbalance = 250 MeV
Total visible energy: 887 MeV (including quenching and e\(^-\) lifetime corrections).
Atmospheric neutrino candidate

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

$$<\varphi> = -0.10 \pm 0.22$$
2011 CNGS run

- 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.
2011 run CC $\nu_e$ event candidate

- 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/π⁰ separation → events seen in a new Bubble chamber like way.

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

- For $1.1 \cdot 10^{20}$ pot: 3000 beam related $\nu_\mu$ CC events expected in ICARUS T600.
  - 7 $\nu_e$ CC intrinsic beam associated events with $E_{\text{vis}} < 20$ GeV → BACKGROUND;
  - 17 $\nu_\tau$ raw CC events assuming $P(\nu_\mu \rightarrow \nu_\tau) = 1.4\% \ (\Delta m^2 = 2.5 \cdot 10^{-3} \text{eV}^2, E_\nu = 20 \text{GeV})$;
  - $P(\tau \rightarrow e\nu\nu) = 18\% \rightarrow 3$ electron deep inelastic events with visible energy $< 20$ GeV → SIGNAL:
    - $\tau \rightarrow e\nu\nu$ events are characterized by momentum unbalance (2ν 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 $\nu_e$ CC events excess).

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

- 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!