The 600 Ton ICARUS detector at the LNGS
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Topics
1. R & D on ICARUS technology detector method
2. Installation of the T600 at the LNGS
3. Physics program: (a) high energy neutrons from CERN, (b) Search for exotic proton decay
4. Possible future plans to search for sterile neutrinos
5. As a prototype for multi-kiloton detector around the world

Summary
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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 sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties

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 form electro-negative molecules ($O_2$, $H_2O$, $C0_2$).
- **Target**: 0.1 ppb $O_2$ equivalent= 3 ms lifetime (4.5 m drift @ $E_{\text{drift}} = 500$ V/cm).
The path to larger LAr detectors

1. 24 cm drift wires chamber
   - CERN

2. 3 ton prototype
   - CERN

3. Laboratory work
   - CERN
   - 50 litres prototype 1.4 m drift chamber
   - 1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4. 10 m³ industrial prototype
   - 1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

5. Cooperation with industry
   - Alinéa, Brome, Cinel, CAEN

6. LNGS Hall-B
   - 2010-2015: Data taking with CNGS beam

T600 detector

Pavia

XIV Int. Workshop on Neutrino Telescopes
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: \( \frac{p}{p} \sim 10\text{-}15\% \) depending on track length and \( p \)

- Measurement of local energy deposition \( dE/dx \):
  - \( e/\pi \) 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 for contained events

RESOLUTIONS

- Low energy electrons: \( \sqrt{E}/E = 11\% / \sqrt{E(\text{MeV})} + 2\% \)
- Electromagnetic showers: \( \sqrt{E}/E = 3\% / \sqrt{E(\text{GeV})} \)
- Hadron shower (pure LAr): \( \sqrt{E}/E \approx 30\% / \sqrt{E(\text{GeV})} \)
Summary of LAr TPC performances

- Tracking device
  - Precise event topology
  - Momentum via multiple scattering
- Measurement of local energy deposition and
  - $e/\gamma$ separation (2$%X_0$ sampling)
  - Particle ID by means of $dE/dx$ vs range
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events

**RESOLUTIONS**

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

*Japan_Dec 2010*
Electrons from muon decay

- Excellent resolution obtained from the measured decay electron spectrum (Michel parameter) from muon decays
The key feature of LAr imaging: very long e-mobility

- The main technological challenge of the development of the cryogenic liquid Ar chamber is the capability of ensuring a sufficiently long free electron lifetime.

- Indeed the free electron path in a liquid is $\approx 600$ times shorter than in a gas. For instance, $10 \text{ ms}$ lifetime corresponds to a $30 \text{ ppt}$ ($t=$trillion!) of Oxygen equivalent.

- At $500\text{v/cm}$, a $5\text{m}$ drift length corresponds to a drift time of $3.1 \text{ ms}$ ($1.6 \text{ m/ms}$).

- The intrinsic bubble size (rms diffusion) is given by

$$\sigma_D[mm] = 0.9 \sqrt{T_D[ms]}$$

- The values for $5\text{m}$ drift are $\langle \sigma_D \rangle \approx 1.1 \text{ mm}$ and $\sigma_{\text{max}} \approx 1.6 \text{ mm}$, tiny with respect to the wire pitch ($\geq 2\text{mm}$).
Reconstruction of $\pi^0$-showers

ICARUS T300 Pavia run

Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.

$M_{\text{inv}} = \sqrt{2E_1E_2 \cos(\theta_{12})}$

$m_{\gamma\gamma} = 133.4 \pm 3.0 \text{(stat)} \pm 4.0 \text{(sys)} \text{MeV/c}^2$

The systematic error mostly due to the calibration
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
  - $HV = -75 \text{ kV}$, $E = 0.5 \text{ kV/cm}$
  - $v_{\text{drift}} = 1.55 \text{ mm/\mu s}$

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

- PMT for scintillation light:
  - $(20+54)$ PMTs, $8'' \varnothing$
  - VUV sensitive (128 nm) with wave shifter (TPB)
Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

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

- $\tau_{ele}$ [ms] = 0.3 / N[ppb O$_2$ equivalent]
- $\tau_R$: recirculation time for a full detector volume
- $k$ and $\tau_I$: related to the total degassing internal rate
- $\tau_R$: 2 m$^3$/h corresponding to $\approx$ 6 day cycle time
- $k_I$: related to the external leaks
ICARUS T600 physics potential

- 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.

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

- “Self triggered” events collection:
  - \( \sim 80 \) events/y of unbiased atmospheric ν CC;
  - zero background proton decay with \( 3 \times 10^{32} \) nucleons for “exotic” channels.
ICARUS and Status of Liquid Argon Technology
Candidate for a $\nu_e$ interaction
Preliminary results of first CNGS 2010 run

- Analyzed sample: 1494 CNGS triggers, i.e. $4.54 \cdot 10^{18}$ pot = 78% out of whole sample. Classified by visual scanning into fiducial volume of 434 t.

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

<table>
<thead>
<tr>
<th>Event type</th>
<th>Collected</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>94</td>
<td>98</td>
</tr>
<tr>
<td>NC</td>
<td>32</td>
<td>31</td>
</tr>
<tr>
<td>XC *</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>132</td>
<td>129</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.
LAr-TPC: powerful technique. Run 9927 Event 572

Total visible energy 4.5 GeV

$p_\mu = 10.5\pm1.1$ GeV/c by multiple scattering

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.

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

<table>
<thead>
<tr>
<th>Track</th>
<th>$E_{d_{eV}}$[MeV]</th>
<th>cosx</th>
<th>cosy</th>
<th>cosz</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>797.7</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></td>
<td></td>
<td></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>
Sterile neutrino search with ICARUS T600

- Appearance search in T600 in LNSD parameter space

- 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 beam contamination, in the deep inelastic interval 10-30 GeV.

- Largely complementary to the Fermi-lab program in terms of energy and baseline.
At these energies, electron identification and energy reconstruction of $\nu_e$ interactions is ensured with $\sim 5 \ X_0 (X_0=14\text{cm})$ longitudinal cut and $\sim 2 \ X_0$ side cut of the sensitive volume are performed, corresponding to a fiducial volume of $\sim 80\%$ of the active one. $\pi^0$ from NC are rejected by photon vertex identification, invariant mass reconstruction and $dE/dx$ measurement: the expected $\pi^0$ mis-interpretation probability is $0.1\%$, with $\nu_e$ detection efficiency of $90\%$ within the fiducial volume.

With these fiducial cuts, the expected $\nu_e$ energy resolution is around $14\%$. 

Two LAr-TPC detectors at the CERN-PS neutrino beam

Two positions are foreseen for the detection of the neutrinos:
The far (ICARUS-T600) location at 850 m from the target: $L/E \sim 1 \text{ km/GeV}$;
The additional detector and new location at a distance of 127 m from the target: $L/E 0.15 \text{ km/GeV}$
Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for $2.5 \times 10^{20}$ pot (30 kW basic option) and twice as much for anti-neutrino (right). The LSND allowed region is fully explored both for neutrinos and anti-neutrinos. The T600 expectations from one year at LNGS are also shown.
Nucleon decay expectations

- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques. It can perform a large variety of exclusive decay modes measurements in bkg free mode.
- With $1.2 \times 10^{34}$ nucleons, MODULAR is well suited for channels not accessible to detectors due to the complicated event topology, or if the emitted particles are below the threshold (e.g. $K^+$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$90%$ CL-5y $(\text{pdg } 90% \text{ CL})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \to \nu \pi^+$</td>
<td>$4.4 \times 10^{-33}$ $(2.5 \times 10^{-31})$</td>
</tr>
<tr>
<td>$p \to \mu^- \pi^+ K^+$</td>
<td>$1.1 \times 10^{-34}$ $(2.5 \times 10^{-32})$</td>
</tr>
<tr>
<td>$n \to e^- K^+$</td>
<td>$1.3 \times 10^{-34}$ $(3.2 \times 10^{-31})$</td>
</tr>
<tr>
<td>$n \to \mu^+ \pi^-$</td>
<td>$6.0 \times 10^{-33}$ $(1.0 \times 10^{-32})$</td>
</tr>
<tr>
<td>$n \to \nu \pi^0$</td>
<td>$4.4 \times 10^{-33}$ $(1.1 \times 10^{-32})$</td>
</tr>
</tbody>
</table>
Detector configuration based on **one or two** double-wall, vacuum-insulated cryostats with the possibility of inside vacuum before filling by LAr.

In order to resist to the outer pressure and vacuum insulation loads the cryostat(s) are built as a 3D array of cubic cells (5m side) without inner common walls to get a continuous LAr active volume across the inner array structure.

Outer vessel linked to the inner one trough thermal bridges (transversally sliding and longitudinally elastic to follow the inner vessel shrinkage).

To get temperature uniformity and minimize updrafts in the active LAr the inner array structure is made by hollow square (or round) beams with inside circulation of LN$_2$ (or dirty LAr) kept liquid by cryogenerators on the top.