LAGUNA: a Joint Liquid Scintillator / Liquid Argon / Water Cherenkov Design Study

André Rubbia (ETH Zürich)

8th International Workshop on Neutrino Factories, Superbeams and Betabeams
UC Irvine (USA) - August 24th-30th, 2006
LAGUNA : Large Apparati for Grand Unification and Neutrino Astrophysics


From MEMPHYS, LENA and GLACIER groups

Open
Large Underground detectors considered in LAGUNA

- Three types of large multi-purpose underground detectors with astrophysical program

- **Water Cherenkov** ($\simeq 0.5 \rightarrow 1 \text{ Mton}$)
  - MEMPHYS

- **Liquid Scintillator** ($\rightarrow 50 \text{ kton}$)
  - LENA

- **Liquid Argon** ($\simeq 10 \rightarrow 100 \text{ kton}$)
  - GLACIER
The need for next generation very large experiments...

A broad particle and astroparticle physics program

- Baryon number violation
- **Astroparticle physics**
  - Gravitational collapse
  - Early alert for astronomers
  - Star formation in the early universe
  - Solar thermonuclear fusion processes
  - Indirect dark matter searches
- **Neutrino properties**
- Geophysical models, Earth density profile

Proton decay

Supernova - $\nu$

Supernova - $\bar{\nu}$

Relic SN - $\nu$

Solar - $\nu$

Muons, $\nu$

Supernova - $\nu$, Atmospheric - $\nu$, Long baseline - $\nu$

Atmospheric - $\nu$

Geo - $\nu$
MEgaton Mass PHYSics (MEMPHYS)

1 shaft ≈ 215 kton H₂O
3 shafts ≈ 500 kton fiducial

≈4xSK

For more details on MEMPHYS, see A. de Bellefon et al., arXiv:hep-ex/0607026.

About 170 γ/cm in 350 < λ < 500 nm
With 40% PMT coverage, Q.E.≈20%
Relativistic particle produces
⇒≈14 photoelectrons / cm
⇒≈7 p.e. per MeV
**Proposed LENA Detector**

**Low Energy Neutrino Astrophysics**

**BOREXINO technology**

PXE ($C_{16}H_{18}$), non-hazard, flashpoint 145°C, density 0.99, ultrapure.
Assumed attenuation length $\approx 12$ m @430 nm

See hep-ph/0605229

**Volume**

$\sim 100$ m length $\times 30$ m $\varnothing$

**Liquid Scintillator**

45,000 ton PXE

**Photomultipliers**

12,000 units 30% surface

**Photoelectron yield**

110 pe/MeV

Timing structure and energy resolution
Giant Liquid Argon Charge Imaging Experiment

GLACIER 100 kton

Electronic crates

$\phi \approx 70\ m$

$h = 20\ m$

Max drift length

Passive perlite insulation

Single module cryo-tanker based on industrial LNG technology

Project: Large Underground Argon Storage Tank

A feasibility study mandated to Technodyne Ltd (UK): Feb-Dec 2004

Could potentially be magnetized
**Nucleon (proton) decay**

- Very challenging still-open goal of particle physics!

1. **Grand-Unification:**
   - Fundamental symmetry between quarks & leptons, transmutation between quarks and leptons: proton unstable
   - Explain electric charges of elementary fermions
   - Help simple models of fermion masses and mixing
   - Motivates SUSY and SUSY predicts LSP as dark matter
   - Motivates see-saw (N_R) and explains tiny neutrino masses

2. **Proton decay**
   - Rate driven by dim-5 & 6 operators and wildly depends on model
   - What are the branching fractions? $p \rightarrow e^+\pi^0$, $\nu K^+$, other decay modes? $\nu \pi^+$, $e\gamma$, $\mu\gamma$, …
Sensitivities of Water and LiqAr to proton decay

p-decay is a bit like the Higgs-boson: we don’t know if it exists nor the mass, but if it does and is within reach, we know what it would look like.
Proton decay search in LENA

See hep-ph/0511230

Event Structure: $p \rightarrow K^+\nu$

$T(K^+) = 105$ MeV
$\tau(K^+) = 12.8$ ns

$K^+ \rightarrow \mu^+\nu_\mu$ 63.43%
$T(\mu^+) = 152$ MeV
$\tau(\mu^+) = 2.2$ $\mu$s
$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$

$K^+ \rightarrow \pi^+\pi^0$ 21.13%
$T(\pi^+) = 108$ MeV
$\tau(\pi^+) = 26$ ns
$T(\pi^0) = 110$ MeV
$\tau(\pi^0) = 8.4 \cdot 10^{-8}$ ns
$\pi^+ \rightarrow \mu^+\nu_\mu$ $\pi^0 \rightarrow \gamma\gamma$

Kaon energy is measured (unlike in Water Cerenkov detectors)
Timing structure and excellent energy resolution reduce backgrounds
How does it compare to theoretical expectation?

Higher dimension models (eg. 6D SO(10)) not included
Definitely not exhaustive.
1. **Supernova physics:**
   - Gravitational collapse mechanism
   - Supernova evolution in time
   - Burst detection
   - Cooling of the proto-neutron star
   - Shock wave propagation
   - Black hole formation?

2. **Neutrino properties**
   - Neutrino mass (time of flight delay)
   - Oscillation parameters (flavor transformation in SN core and/or in Earth): Type of mass hierarchy and $\theta_{13}$ mixing angle

3. **Early alert for astronomers**
   - Pointing to the supernova
Supernova detection in WC

![Graph showing supernova detection rates](image)

**Complementarity**

380 $\nu_e$ events with oscillations at $d=10\text{kpc}$

$\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^+ + e^-$  $Q=1.5 \text{ MeV}$

$\overline{\nu}_e + ^{40}\text{Ar} \rightarrow ^{40}\text{Cl}^+ + e^+$  $Q=7.48 \text{ MeV}$

$(-)^{\nu}_e + ^{40}\text{Ar} \rightarrow ^{40}\text{Ar}^* + \nu_x$  $Q=1.46 \text{ MeV}$

$(-)^{\nu}_x + e^- \rightarrow \nu_x + e^-$

**Scenario I:** expected events in 100 kton detector

$\langle E_{\nu_e} \rangle = 11 \text{ MeV}$, $\langle E_{\nu_x} \rangle = 16 \text{ MeV}$, $\langle E_{\nu_x} \rangle = \langle E_{\nu_x} \rangle = 25 \text{ MeV}$

and luminosity equipartition

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Without oscillation</th>
<th>Oscillation (n.h.)</th>
<th>Oscillation (i.h.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_{13}$</td>
<td>$\theta_{13}$</td>
<td>$\theta_{13}$</td>
</tr>
<tr>
<td>ELAS</td>
<td>1330</td>
<td>1330</td>
<td>1330</td>
</tr>
<tr>
<td>$\nu_e$, CC</td>
<td>6240</td>
<td>31320</td>
<td>28320</td>
</tr>
<tr>
<td>$\overline{\nu}_e$, CC</td>
<td>540</td>
<td>1110</td>
<td>1110</td>
</tr>
<tr>
<td>NC</td>
<td>30440</td>
<td>30440</td>
<td>30440</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>38550</td>
<td>64200</td>
<td>56700</td>
</tr>
</tbody>
</table>

**Possibility to statistically separate the various channels by a classification of the associated photons from the $K$, $Cl$ or $Ar$ deexcitation (specific spectral lines for CC and NC) or by the absence of photons (ES)**
**Supernova neutrino detection in 50 kton scintillator**

- $\bar{\nu}_e + p \rightarrow n + e^+ \ (Q=1.8 \ MeV)$
  
  $n + p \rightarrow d + \gamma; \quad E_\gamma = 2.2 \ MeV \quad \sim 8700 \ events$

- $\bar{\nu}_e + ^{12}\text{C} \rightarrow ^{12}\text{B} + e^- + \ (Q=17.3 \ MeV)$
  
  $^{12}\text{B} \rightarrow ^{12}\text{C} + e^+ + \bar{\nu}_e; \quad \tau_{1/2} = 20.20 \ ms \quad \sim 494 \ events$

- $\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N} \ (Q=13.4 \ MeV)$
  
  $^{12}\text{N} \rightarrow ^{12}\text{C} + e^+ + \nu_e; \quad \tau_{1/2} = 11.00 \ ms \quad \sim 85 \ events$

- $\nu_x + ^{12}\text{C} \rightarrow ^{12}\text{C}^* + \nu_x$
  
  with $^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma; \quad E_\gamma = 15.11 \ MeV \quad \sim 2925 \ events$

- $\nu_x + e^- \rightarrow \nu_x + e^- \ (\text{elastic scattering}) \quad \sim 610 \ events$

- $\nu_x + p \rightarrow \nu_x + p \ (\text{elastic scattering})$
  
  Detector energy threshold: $E_{th} = 0.2 \ MeV \quad \sim 7370 \ events$

Event rates for a SN type IIa in the galactic center (10 kpc)

*Total $\approx 20000 \ events$*
Relic supernova neutrinos

We need information concerning...

1. Neutrino spectrum emitted from each supernova explosion
2. Neutrino oscillation within supernovae and the Earth
3. Supernova rate

\[
\frac{dE_{\nu}}{dE_{\nu}} = c \int_0^{z_{\text{max}}} R(z) \frac{dN_{\nu}(E, z)}{dE} (1 + z) \frac{dt}{dz}
\]

In LENA detector:
(44 kt fiducial volume)
- \(\bar{\nu}_e + p \to n + e^+\)
- \(n + p \to d + \gamma\)
- \(E_\gamma = 2.2 \text{ MeV}\)

Event rate in 10 y:
- LL: \(\sim 42 \text{ events}\)
- TBP: \(\sim 20 \text{ events}\)
(discrimination power at 90% C.L.)

See Vagins et al, \textit{GADZOOKS}

\(\nu_e + ^{40}\text{Ar} \to ^{40}\text{K}^* + e^-\)

16 MeV \(\leq E_e \leq 40 \text{ MeV}\)

<table>
<thead>
<tr>
<th>mass hierarchy</th>
<th>(\theta_{13})</th>
<th>(P(\nu_e \to \nu_e))</th>
<th>(P(\nu_e \to \bar{\nu}_e))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>normal</td>
<td>large</td>
<td>(\sin^2 \theta_{13})</td>
</tr>
<tr>
<td>II</td>
<td>inverted</td>
<td>large</td>
<td>(\sin^2 \theta_{12})</td>
</tr>
<tr>
<td>III</td>
<td>normal/inverted</td>
<td>small</td>
<td>(\sin^2 \theta_{12})</td>
</tr>
</tbody>
</table>

57 events for 500 kton-years and scenario I (4\(\sigma\))
43 events for 500 kton-years and II or III
1. Atmospheric neutrinos:
   - High statistics, from observation to precision measurements
   - L/E dependence
   - Sterile neutrinos and tau appearance
   - Electron appearance $\theta_{13}$
   - Earth matter effects and sign of $\Delta m^2_{23}$
   - CP-violation

2. Solar neutrinos
   - High statistics, precision measurement of flux
   - D/N asymmetry
   - Time variation of flux
   - Solar flares
   - ...
1. **Geophysics:**
   - Test the U/Th/K content in Earth (mantle, core)
   - How much heat is primordial?
   - Get the distribution of radioactive elements through the earth
   - Test if there are radioactive elements in the core (\(^{40}\text{K}\)?)
   - Any other (nuclear reactor in core?)

2. **In particular, HEAT**
   - What is the source of terrestrial heat flow?
   - Understanding Earth’s heat is fundamental for explaining many phenomena like e.g. volcanoes, earthquakes, …
**Outstanding non-accelerator physics goals**

*Comparison among liquids: which combination provides maximal physics output?*

<table>
<thead>
<tr>
<th></th>
<th>Water Cerenkov</th>
<th>Liquid Argon TPC</th>
<th>Liquid Scintillator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total mass</strong></td>
<td>500 kton</td>
<td>100 kton</td>
<td>50 kton</td>
</tr>
<tr>
<td><strong>p → e π^0 in 10 years</strong></td>
<td>1.2x10^{35} years</td>
<td><strong>ε</strong> = 17%, ≈ 1 BG event</td>
<td>0.5x10^{35} years</td>
</tr>
<tr>
<td><strong>p → νK in 10 years</strong></td>
<td>0.15x10^{35} years</td>
<td><strong>ε</strong> = 8.6%, ≈ 30 BG events</td>
<td>1.1x10^{35} years</td>
</tr>
<tr>
<td><strong>SN cool off @ 10 kpc</strong></td>
<td>194000 (mostly ν_e p → e^+n)</td>
<td>38500 (all flavors) (64000 if NH-L mixing)</td>
<td>20000 (all flavors)</td>
</tr>
<tr>
<td><strong>SN in Andromeda</strong></td>
<td>40 events</td>
<td>7</td>
<td>4 events</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(12 if NH-L mixing)</td>
<td></td>
</tr>
<tr>
<td><strong>SN burst @ 10 kpc</strong></td>
<td>≈250 ν-e elastic scattering</td>
<td>380 ν_e CC (flavor sensitive)</td>
<td>≈30 events</td>
</tr>
<tr>
<td><strong>SN relic</strong></td>
<td>250(2500 when Gd-loaded)</td>
<td>50</td>
<td>20-40</td>
</tr>
<tr>
<td><strong>Atmospheric neutrinos</strong></td>
<td>56000 events/year</td>
<td>≈11000 events/year</td>
<td>5600/year</td>
</tr>
<tr>
<td><strong>Solar neutrinos</strong></td>
<td>91250000/year</td>
<td>324000 events/year</td>
<td>?</td>
</tr>
<tr>
<td><strong>Geoneutrinos</strong></td>
<td>0</td>
<td>0</td>
<td>≈3000 events/year</td>
</tr>
</tbody>
</table>

*Clear complementarity between techniques!*
**Neutrino properties (with accelerators)**

1. **Precision measurement:**
   - Precision measurement of \((\theta_{23}, \Delta m^2_{32})\) with error < 1%

2. **Discoveries**
   - \(\theta_{13}\)
   - \(\delta_{CP}\)
   - \(\text{sign}(\Delta m^2_{32})\)
Outstanding physics has a cost...

- “The cost of knowledge”
- Detector costs w/o excavation:
  - MEMPHYS $\approx 350 \text{ M€} / 500 \text{ kton fiducial}$
  - GLACIER $\approx 300 \text{ M€} / 100 \text{ kton}$ (including merchant price of 100 kton of LAr)
  - LENA $\approx 150 \text{ M€} / 50 \text{ kton}$
- Excavation underground laboratory assuming good rock quality (J. Peltoniemi):
  - Underground laboratory: typ. 200 €/m$^3$
  - Access construction
    - Wide decline (tunnel, ramp) with heavy truck access: 2000€/m
    - Narrow tunnel: 1000 €/m
    - Shaft (7m) 5000 €/m, (2m) 1000 €/m
    - Dedicated lift to surface: 2-10 M€
  - Detector cavern:
    - MEMPHYS: 240M€ (Fréjus study)
    - GLACIER: 10-30 M€ depending on depth
    - LENA: 10-15 M€ deep underground
- Scale of cost / project $\approx 200\text{-}600 \text{ M€}$
  - According to industry, $\approx 10\%$ of final cost should be devoted to design!

\[ FOM = \frac{M \€}{\text{€}} \]
ApPEC is the Astroparticle Physics Coordination in Europe (similar to ECFA, NuPEC, CERN SG). Represents large funding agencies for APP in Belgium, France, Germany, Greece, Italy, Netherlands, Spain, Switzerland and UK (soon Poland).

The ASPERA ERA-Net (European Research Area-Network) of ApPEC has been funded and gives a “legal status” to ApPEC. Through it, national Funding Agencies are committed to spend fraction of their budgets in common projects.

- **In the pipeline:** KM3 in Mediterranean, CTA for HE $\gamma$ astronomy, GW detection

The ApPEC Steering Committee has mandated the Peer Review Committee to write a Roadmap. The ApPEC roadmap recommendation concerning large neutrino detectors:

- **We recommend that a new large European infrastructure is put forward, as a future international multi-purpose facility on the $10^5$-$10^6$ ton scale for improved studies of proton decay and of low-energy neutrinos from astrophysical origin. The three detection techniques being studied for such large detectors in Europe, Water-Cherenkov, Liquid Scintillator and Liquid Argon, should be evaluated in the context of a common design study which should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams. This design study should take into account worldwide efforts and converge, on a time scale of 2010, to a common proposal.**

The design study could lead to the European Strategy Forum on Research Infrastructures (ESFRI) process.
LAGUNA is a coordinated European effort

- At the ApPEC “Munich meeting” held on November 2005, a coordinated effort among the 3 “liquids” has been proposed and accepted. Large detectors like Water Cherenkov, Liquid Scintillator and Liquid Argon present important physics complementarities and also a lot of common R&D needs. They have to work in synergy.

- The purpose is to develop conceptual designs for European large scale liquid detectors into coherent and well-coordinated EU wide efforts towards a common physics goal and solving common problems together, taking into account the unique technological expertise in Europe and the other existing or planned programs in the world, such that mature designs and credible scenarios can be proposed around 2010.

- During the last months, an effort has been made to consolidate these ideas into a format compatible with potential EU Framework Programme FP7 instruments. The idea is to submit a common EU design study on the three liquids by beginning of 2007.

- This effort, although oriented towards a potential infrastructure in Europe, should allow Europeans to contribute in a coherent way and possibly with better impact, to the on-going discussions worldwide (e.g. NNN workshops).
LAGUNA DS: Progress report

- ApPEC Town-Meeting Munich, November 2005
- A series of working meeting were held
  - Munich, 24th of April 2006
  - Munich, 2nd of June 2006
  - Paris, 21st of July 2006
  - Next: Zurich, October 12th, 2006

- A scientific case document (≈50 pages) has been drafted.

- A detector conceptual design document is meant to be prepared.

- A list of preliminary Working Packages, in a possibly suitable form for the FP7 DS, has been prepared.

- The FP7 DS request has to be written until beginning 2007 (depending on exact time schedule of EU).
**Proposed working packages for LAGUNA DS**

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<th>WP1: Tank instrumentation</th>
<th>Light/charge detection, electronics, HV</th>
</tr>
</thead>
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<tr>
<td>WP2: Underground tanks</td>
<td>Design, geometry, support structure, materials, insulation, underground assembly</td>
</tr>
<tr>
<td>WP3: DAQ &amp; Calibration</td>
<td>DAQ, data analysis, slow controls</td>
</tr>
<tr>
<td>WP4: Cosmics, Local Backgrounds, Materials</td>
<td>In-situ measurements, external/internal backgrounds, simulations, coordination with ILIAS</td>
</tr>
<tr>
<td>WP5: Sites</td>
<td>Feasibility of large excavations, access, local conditions, site preselection</td>
</tr>
<tr>
<td>WP6: Liquids</td>
<td>Production, handling, purification, filling, long-term stability, gases</td>
</tr>
<tr>
<td>WP7: Safety &amp; environment</td>
<td>Infrastructure, risk analysis (earthquakes, fire, liquid evaporation, …)</td>
</tr>
<tr>
<td>WP8: Physics &amp; simulations</td>
<td>Physics potential of the facility</td>
</tr>
</tbody>
</table>
WP1

Tank Instrumentation

Addressing scaling-up issues
(mainly cost)
R&D on photodetection (MEMPHYS)
(industrial reduction of cost)

• Common R&D IN2P3-PHOTONIS in the context of a “GIS” (PHOTONIS recently acquired DEP and BURLE)

• Axes of collaboration:
  • Smart ensembles (all electronics up to ethernet included) of standard 12” photodetectors. A cost minimum?
  • Flat UV detectors for LiqAr
• Trying to lower the industrial cost is fundamental

• HAMAMATSU develops HPD’s
• BURLE truncated bulb PMT’s

Table 3: Preliminary cost estimate of the MEMPHYS detector

<table>
<thead>
<tr>
<th></th>
<th>3 Shafts</th>
<th>Total cost of 250k 12” PMTs</th>
<th>Infrastructure</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 ME</td>
<td>250 ME</td>
<td>100 ME</td>
<td>590 ME</td>
<td></td>
</tr>
</tbody>
</table>

- Diameter: 20” <= 12”
- Projected area: 1660 cm²
- QE (typ): 20% = 24% cm³
- CE: 60% = 70%
- Cost: 2500 = 800 €
- Cost/p.e/cm: 13 = 8 €

New bulb design: “Truncated bulb”
> Uniform E-field in front of cathode
> Small neck
> TTD ~ 1.5 ns

Goal:
> Fully automatic production of 20” PMTs
> Aim ~ $1,500/PMT
R&D on scalability of liquid Argon detectors (GLACIER)

Charge readout with extraction & amplification for long drifts

ArgonTube: 5 m drift test

Electronic racks

Field shaping electrodes

E ≈ 3 kV/cm

E ≈ 1 kV/cm

UV & Cerenkov light readout photosensors

Greinacher voltage multiplier up to MV

Large area DUV sensitive photosensors
**Charge readout: Thick Large Electron Multiplier (LEM)**

Thick-LEM: Vetronite with holes, coated with copper
- macroscopic GEM
- easier to operate at cryogenic temperatures
- hole dimensions: 500 µm diameter, 800 µm distance

- Thickness: 1.5 mm
- Amplification hole diameter = 500 µm
- Distance between centers of neighboring holes = 800 µm
- Distance between stages: 3 mm
- Avalanche spreads into several holes at second stage
- Higher gain reached as with one stage, with good stability
Shapes from Fe$^{55}$ radioactive source (5.8 keV, event rate about 1kHz) of the signals from double-stage LEM system have a very clean S/N ratio.

This technique solves the non-scalability of the traditional wire readout used in ICARUS. E.g. MIP signal @ $\approx$2 MeV/cm has poor S/N!

Full imaging TPC with LEM to be tested in 1 ton prototype @ CERN
Long drift, extraction, amplification: “ARGONTUBE”

- Full scale measurement of long drift (5 m), signal attenuation and multiplication
- Simulate ‘very long’ drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 500 kV)
- Measurement Rayleigh scatt. length and attenuation length vs purity
- Design & assembly: completed: external dewar, detector container in progress: digging of hole in ground, ...
Large number of channels waveform digitizers

- fC-sensitive charge preamplifier
- Waveform digitizer with Ms/s sampling rate
- Zero suppression
- No dead-time
- Embedded processor for high level data compression and network connection
- Many channels / unit
- Affordable (<50€/channel)

Need >100K channels
WP2

Underground Tanks

Study the constructability large underground tanks
Study their operability underground
Tanks above surface

- Rules defined in Part 4-2 of EUROCODE 3 (EUROCODES = The rules for design in civil engineering on a new, pan-European basis)
- Provides principles and application rules for the structural design of vertical cylindrical above ground steel tanks for the storage of liquid products with the following characteristics
  - Characteristic internal pressures above the liquid level not less than -100mbar and not more than 500 mbar
  - Design metal temperature in the range of -50°C to +300°C. For tanks constructed using austenitic stainless steel, the design metal temperature may be in the range of -165°C to +300°C;
  - Maximum design liquid level not higher than the top of the cylindrical shell.
  - EN 1993-4-2 is concerned only with the requirements for resistance and stability of steel tanks. Other design requirements are covered by

  - prEN 14015 for ambient temperature tanks;
  - prEN 14620 for cryogenic tanks;
  - prEN 1090 for fabrication and erection considerations. These other requirements include foundations and settlement, fabrication, erection and testing, functional performance, and details like man-holes, flanges, and filling devices.

- Provisions concerning the special requirements of seismic design are provided in EUROCODE 8, Part 4, which complements the provisions of EUROCODE 3 specifically for this purpose. The design of a supporting structure for a tank is dealt with in EN 1993-1-1. The design of an aluminum roof structure on a steel tank is dealt with in EN 1999-1-5.
Study of large underground storage tank

A feasibility study mandated to Technodyne LtD (UK): a unique opportunity!

Study duration: February - December 2004

Project: Large Underground Argon Storage Tank

Contents
1 Introduction
2 Requirement
3 Tank design
4 Full Containment
5 Cavern considerations
6 Process considerations
7 Safety issues
8 Budgetary costing
9 Tank
10 Contents

Current LNG Storage Tank Designs
4.1 Single Containment
4.2 Double Containment
4.3 Membrane
4.4 Construction considerations
4.5 Insulation considerations
4.6 Underground LAr tank design

Cavern considerations
6.1 Initial fill
6.2 Re-Liquefaction of the boil-off
6.3 Purification of the Liquid Argon

Safety issues
7.1 Stability of cavern
7.2 Seismic events
7.3 Catastrophic failure of inner tank
7.4 Argon gas leaks

Budgetary costing
8.1 Tank
8.2 Contents
9 Contents
Tanks located underground

- Worldwide for LNG storage the largest above ground tank that has been built to date is the 180,000m³ tank at Senboku Japan. The industry also perceives the requirement to increase the capacity to above 200,000m³ in the near future. It is feasible to increase the tank capacities of Concrete / 9% Ni Steel storage tank designs to capacities above 200,000 m³.

- Underground tanks contemplated for physics experiments are relatively small compared to those used by the petro-chemical industry for above ground storage of materials.

- **Outcome of study with Technodyne:** The principles used in the design of above ground storage tanks should be readily transferable to an underground scenario.

- Extra considerations will obviously have to be taken into account when underground however, other design considerations such as wind loading and solar heating effects are eliminated from the above ground case.
Underground construction

- In an above ground scenario the large tanks described above are usually constructed using common civil construction techniques. As there is no restriction on headroom the use of large cranes is normal. In the underground scenario it is less likely that there will be enough headroom to allow the use of large cranes. The domed roof is normally constructed on the bottom of the tank and then raised and welded in place using air pumped into the vessel.

- This technique is commonly used when manufacturing these types of tank and does not present a problem underground. The only requirement being a supply of electricity to power the air fans needed to raise the roof.

- An alternative technique could then to be employed where the roof is built first together with the top ring of the shell. The assembly would then be jacked up about 3m and the next lower ring installed. Successive ring welding / jacking operations would be performed until the shell is completed without the use of a large crane. This is a common technique for large diameter oil storage tanks.

- The order of construction of the tank would be as follows:
  1. Base
  2. Roof and deck
  3. Outer shell
  4. Base insulation
  5. Inner shell base
  6. Inner shell
  7. Insulation
Erection of a tank above surface

1. Concrete base
2. Concrete outer-shell
3. Roof assembly
4. Air-raising
The estimated costs tabulated below are for an inner tank of radius 35m and height 20m, an outer tank of radius 36.2m and height 22.5m. The product height is assumed to be 19m giving a product mass of 101.8 k tonnes.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Size</th>
<th>Million Euros</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steel</td>
<td>3400 tonnes</td>
<td>11.6</td>
</tr>
<tr>
<td>2</td>
<td>Insulation</td>
<td>16200 m³</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>Concrete</td>
<td>9000 m³</td>
<td>2.7</td>
</tr>
<tr>
<td>4</td>
<td>Electro-polishing</td>
<td>38000 m² Plate</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.5 km weld</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Construction design / labour</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Site equipment / infrastructure</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>53.7</td>
</tr>
<tr>
<td>6</td>
<td>Underground factor</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Underground tank cost</td>
<td></td>
<td>107.4</td>
</tr>
</tbody>
</table>

Design study will address additional cost for underground construction

Too conservative?
WP5

Sites

Study the feasibility of very large excavations including access
Compare local conditions
Pre-select suitable sites
WP5: Site investigation

- Work closely with Integrated Large Infrastructure for Astroparticle Science ILIAS-N2-WG1
  - And respective WG in ILIAS-next
  - ILIAS N2: propose to organise a technical meeting on site expansions and technical issues in November 2006

- Pre-feasibility studies
  - Partially done (Fréjus, Pyhäsalmi)
  - Extend to LNGS, Sieroszowice, …
  - Green fields
  - Report on constructability: possible show-stoppers

- Feasibility studies (for all sites)
  - Including thorough rock sampling, rock simulations
    - Pre-plan for construction
    - Cost estimates
    - Site pre-selection

- Final goal ⇒ Detailed plans for site construction
Currently there is no available site to host very large scale detectors in Europe!

- New facilities will have to be excavated or old one extended
- What depth?
- What other synergies? (beamline distance)
- What is the distance from reactors?
# Very preliminary sites vs experiments

<table>
<thead>
<tr>
<th></th>
<th>Mt Water Cerenkov</th>
<th>Liquid Scintillator</th>
<th>Liquid Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fréjus</td>
<td>Tunnel / hard rock</td>
<td>✓ ✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Gran Sasso</td>
<td>Tunnel / soft rock</td>
<td>✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Canfranc</td>
<td>Tunnel</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Pyhäsalmi</td>
<td>Mine / hard rock</td>
<td>✓</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>Boulby</td>
<td>Mine / salt (potash)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Polkowice - Sieroszowice</td>
<td>Mine / salt &amp; rock</td>
<td>✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Green fields</td>
<td>Own shaft / Hard rock</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ ✓ ✓ primary interest; ✓ ✓ probably; ✓ unlikely; ? unknown
Pre-feasibility study in the central region of Fréjus tunnel

Excavation engineering pre-study has been done by SETEC & STONE companies

1) the best site (rock quality) is found in the middle of the mountain, at a depth of 4800 mwe: a really good chance!

2) of the two considered shapes: “tunnel” and “shaft”, the “shaft (= well) shape” is strongly preferred

3) Cylindrical shafts are feasible up to:
   a diameter $\Phi = 65$ m and a full height $h = 80$ m ($\approx 250000$ m³)

4) with “egg shape” or “intermediate shape” the volume of the shafts could be still increased

5) The estimated cost is $\approx 80$ M€ × Nb of shafts

Scenarios:
- 3 shafts $\approx 450$ ktons H₂O
- 4 shafts $\approx 600$ ktons H₂O
- +1 shaft $\approx 100$ kton LAr?
Sieroszowice mine (Poland) - big salt cavern

Copper - 6th position in the world’s exploitation ranking

Silver - 2nd position
But also Salt

Volume (100x15x20) m³
Depth ~950 m from a surface
Salt layer ~70 m thick
Temperature ~35°C
Very good radioactive background conditions

A. Zalewska
Example: baselines from CERN

\[ L = 630 \text{ km} \]
\[ L = 130 \text{ km} \]
\[ L = 732 \text{ km} \]
\[ L = 2300 \text{ km} \]
\[ L = 950 \text{ km} \]
If rock is well known and very good quality in a given site, a new hole in virgin ground can be considered:
• 200 m depth relatively “easy”
• Excavation cost ≈ 5-10 M€ for shaft and ≈20M€ for 100 kton LAr experimental hall
• 1400 m possible ≈ +20 M€

(J. Peltoniemi)

total crossing muons (E> 1GeV) per 10ms

Fiducial mass after slice of size D around each muon is vetoed

D=10 cm

Surface 13000
50 m 100
188 m 3.2
1 km w.e 0.65
2 km w.e 0.062
3 km w.e 0.010

Example of occupancy in LAr @ 50 m underground:

2D view 50 m underground

2700 channels = 8.1 m

2500 samples = 2.5 m
Outlook
Overall picture of activities (and dreams…)

Upgrade existing machines (LHC luminosity)
High intensity proton source
(HIPPI, SPL, PS+, …)

Superbeam

Neutrino factory

CERN SG

ISS/NF DS

EURISOL

Betabeam

EURISOL DS

NuPEC

Very large underground labs
Large underground detectors
Non accelerator physics

LAGUNA DS

ApPEC

SPL  330
EURISOL  200
PS upgrade  150
Superbeam  70
β decay ring  340
Lab + detectors  500
Total  1500

Rough cost in M€ (no manpower, no contingencies)
Outlook

- Around 2011-2012 after a few years of running of LHC and T2K&NovA, there will be a new landscape concerning supersymmetry, unification, and hopefully the last unknown neutrino mixing angle $\theta_{13}$.

- These will also be the times of world distribution of new very large infrastructures.

- Large detectors like Water Cherenkov, Liquid Scintillator and Liquid Argon present important physics complementarities (e.g. flavours of proton decay, type of neutrinos in supernova searches) and also a lot of common R&D needs (cavities, photodetection). They will work in synergy.

- In Europe a common design study for FP7 will help reach the required critical mass needed to study the three options with the required level of details. Worldwide coordination (e.g. NNN workshops) will benefit from a better coordinated EU effort.

- The large underground detector physics program concerns both non-accelerator/astroparticle physics and neutrino accelerator physics. THIS IS A GREAT ASSET and it will be taken properly into account.
Backup slides
### Possible sequence of events

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
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<td><strong>R&amp;D</strong></td>
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<td><strong>Prototype</strong></td>
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<tr>
<td>(existing site, shallow depth?)</td>
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<td><strong>Staged detector</strong></td>
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<tr>
<td>(new site, underground or shallow depth, window of opportunity?)</td>
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<tr>
<td><strong>Ultimate facility</strong></td>
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<tr>
<td>(new very large underground or shallow depth site, one such facility in the world)</td>
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<td><strong>T2K, NoVA</strong></td>
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<td><strong>Colliders</strong></td>
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<td><strong>DM-direct</strong></td>
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<td><strong>Physics</strong></td>
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<td>Physics: p-decay, SN, …</td>
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<tr>
<td>complementary to SK</td>
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<td><strong>Superbeam?</strong></td>
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<td><strong>“Megaton” physics</strong></td>
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<td>CP-violation, $\text{sgn}(\Delta m^2)$</td>
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<td>$\beta$-beam, NF ?</td>
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<td><strong>Evidence for SUSY → GUT → p-decay</strong></td>
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<td><strong>DM-direct</strong></td>
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<td>WIMPS ?</td>
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<td><strong>DM-direct</strong></td>
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<td>WIMPS ?</td>
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<td>Item</td>
<td>100 kton</td>
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<td>------------------------------------------------</td>
<td>------------</td>
<td>-----------</td>
<td></td>
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<tr>
<td>LNG tanker (see notes 1-2)</td>
<td>50÷100</td>
<td>20 ÷ 30</td>
<td></td>
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<tr>
<td>Merchant cost of LAr (see note 3)</td>
<td>100</td>
<td>10</td>
<td></td>
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<tr>
<td>Refilling plant</td>
<td>25</td>
<td>10</td>
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<td>Purification system</td>
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<td>Civil engineering + excavation</td>
<td>30</td>
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<td>Forced air ventilation</td>
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<td>Safety system</td>
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<tr>
<td>Inner detector mechanics</td>
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<td>3</td>
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<td>Charge readout detectors</td>
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<td>5</td>
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<tr>
<td>Light readout</td>
<td>60 (with Č)</td>
<td>2 (w/o Č)</td>
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<td>Readout electronics</td>
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<td>5</td>
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<tr>
<td>Miscellanea</td>
<td>10</td>
<td>5</td>
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<td></td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>340 ÷ 390</strong></td>
<td><strong>≈ 80 ÷ 90</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
(1) Range in cost of tanker comes from site-dependence and current uncertainty in underground construction
(2) Cost of tanker already includes necessary features for LAr TPC (surface electropolishing, hard roof for instrumentation, feed-throughs,…)
(3) LAr Merchant cost ≠ production cost. Fraction will be furnished from external companies and other fraction will be produced locally (by the refilling plant)
Small scale test of a 10 lt LAr TPC embedded in a B-field

First real events in B-field ($B=0.55T$):

New test: small test solenoid built wit HTS wire (American Superconductor)

Made of 4 pancakes, total HTS wire length: 80m

<table>
<thead>
<tr>
<th></th>
<th>LN$_2$ (77K)</th>
<th>LAr (87K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. applied current</td>
<td>145 A</td>
<td>80 A</td>
</tr>
<tr>
<td>On-axis B-field</td>
<td>0.2 T</td>
<td>0.11 T</td>
</tr>
<tr>
<td>Coil resistance at 4A</td>
<td>6 $\mu$Ω</td>
<td>6 $\mu$Ω</td>
</tr>
</tbody>
</table>