Detectors for the Next Generation of Neutrino Beams

A. Marchionni, ETHZ
NuFact’11, Geneva, 1-6 August 2011

- **Detector technologies**
  - Magnetized Iron, Water-Cherenkov, Totally Active Scintillator, LAr TPC

- **Accelerator neutrino beams**
  - SuperBeams, Beta Beams, Neutrino Factory

- **Additional fundamental physics?**
  - Astrophysical neutrino sources, rare processes

- **Extrapolation from present detectors**
  - just ‘the bigger than the past the better’? New approaches, more segmentation, more fine-grained, magnetization?

- **Detector R&D**
  - photodetectors, LAr technology

- **Some concluding thoughts**
Present neutrino detectors

- Super-Kamiokande
- ICARUS
- MINOS
- NOvA (near detector)
- TCSD
- MIND
- LAr TPC
...and their events

$v_e$ candidate event

visible energy : 1049 MeV  
# of decay-$e$ : 0  
2$\gamma$ Inv. mass : 0.04 MeV/c$^2$  
recon. energy : 1120.9 MeV
Next generation of neutrino beams

- **SuperBeams** (MWatt scale proton beam power)
  - mainly $\pi^+ \rightarrow \mu^+ \nu_\mu$, with $\nu_e$ contamination from $\mu$ and $K$ (~0.5-1%)
  - from wide-band to off-axis beams: tuning of $\nu$ beam peak energy and width
  - main channels: $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$

- **or strict selection and acceleration of neutrino parent**

- **Beta Beams**
  - pure $\nu_e / \bar{\nu}_e$ from radioactive beta decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>$^6$He</th>
<th>$^{18}$Ne</th>
<th>$^8$Li</th>
<th>$^8$B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (MeV)</td>
<td>3.5</td>
<td>3.0</td>
<td>13.0</td>
<td>13.9</td>
</tr>
</tbody>
</table>

- **Neutrino factory Beams**
  - $\nu$ beams from $\mu$ decays in a storage ring $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
  - Baseline option: $E_\mu = 25$ GeV
  - Low Energy NF: $E_\mu = 4$-5 GeV

  - main channels: $\nu_e \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$

- golden $\nu_e \rightarrow \nu_\mu$
- silver $\bar{\nu}_e \rightarrow \nu_\tau$
- platinum $\bar{\nu}_\mu \rightarrow \nu_e$
Additional fundamental physics with a large neutrino detector?

- **Baryonic number violation**
  - proton decay searches are a primary tool to address physics at the GUT scale (as well as ν masses and mixing)

- **An observatory for astrophysical neutrinos** (in order of decreasing energy)
  - atmospheric neutrinos
    - direct detection of ντ in atmospheric neutrinos
  - supernova core collapse neutrinos
  - diffuse supernova neutrino background
  - solar neutrinos
  - geo-neutrinos

- **Astrophysical neutrino sources could still be important for the determination of neutrino properties**

A neutrino detector sensitive to $\bar{\nu}_e$ down to ~10 MeV would also be capable of measuring $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ from a $\mu^+$ decays at rest source generated by high intensity cyclotrons (Daedalus proposal)
Magnetized Iron Neutrino Detector

- 2 sections, each 15m long
- tracking calorimeter with interleaved planes of steel and solid scintillator
- total of 486 layers of 2.54 cm Fe planes, 8 m wide
- 1 cm thick and 4.1 cm wide solid scintillator strips with WLS fiber readout
- 25800 m² active detector planes
- ~1.5 T toroidal magnetic field
- longitudinal granularity 1.5 $X_0$
- 5.4 kton total mass

- 14 m x 14 m steel plates, 3.0 cm thick
- 100 kA-turn for magnetization using Superconducting Transmission Lines, providing a toroidal field between 1 T and 2.2 T
- Fe/Sci = 3 cm/2 cm (2 planes of scintillator, with 1 cm x 3.5 cm cross section)
- 50 m – 100 m length → 50 kton – 100 kton
MIND efficiency and background rejection

MIND response to the golden channel (wrong sign muons)

Main background from mis-identification of $\nu_\mu$ ($\bar\nu_\mu$) CC interactions as the opposite polarity

$\sim 10^{-4}$
Super-K
Total volume 50 kton
Fiducial 22.5 kton
11129 20" ID PMTs
40% coverage
1885 8" OD PMTs

Hyper-K (current baseline)
1Mton total vol.
540kton fiducial vol.
Inner Detector \{D43m \times L(5x50m)\} \times 2
PMT \sim 100,000 (20inch)
(Photo-coverage 20%)
...or with vertical tanks

**LBNE DUSEL**
- **Water Tank**
  - 53m Dia. x 54m vertical
- **Fiducial Volume**
  - 50m Dia. x 51m vertical

**LAGUNA – Frejus MEMPHYS**

2 independent modules,
330000 m³ each
220000 8-10" PMTs
≈ 500 kton fiducial mass
NOvA achieves 35% efficiency for $\nu_e$ CC while limiting NC→$\nu_e$ CC fake rate to 0.1%
Totally Active Scintillator Detector (segmented) II


Superconducting Transmission Line could be used to construct large solenoids (15 m φ, 75 m long) capable of producing 0.5 T field

20 kt fiducial mass = 1.33x NOvA
6.7M channels = 20x NOvA
Totally Active Scintillator Detector (non-segmented)

**Borexino**

- active mass of 278 tons of pseudocumene, doped with PPO

**LEN A**

- Target volume
  - height 100 m
  - diameter 26 m
  - 50 kton liquid scintillator

- Shielding from cosmics: 4000 m.w.e.

- Geoneutrinos
- Solar neutrinos
- Supernova burst neutrinos, diffuse supernova neutrinos
- Proton Decay
- Tracking capability being investigated for use with $\nu$ beams
From bubble chamber to LAr TPC

Gargamelle Bubble Chamber
3 ton sensitive mass
Heavy Freon

Bubble $\varnothing$ (mm)  3
Density (g/cm$^3$)  1.5
$X_0$ (cm)  11.0
$\lambda_T$ (cm)  49.5
dE/dx (MeV/cm)  2.3

2.7 ton drift chambers
target
Density (g/cm$^3$)  0.1
2% $X_0$/chamber
0.4 T magnetic field

TRD detector
Lead glass calorimeter

Resolution (mm$^3$)  3×3×3
Density (g/cm$^3$)  1.4
$X_0$ (cm)  14.0
$\lambda_T$ (cm)  54.8
dE/dx (MeV/cm)  2.1

ICARUS 600 ton

C. Rubbia,
CERN Report 77-8,
May 1977
**Concepts for large LAr TPC**

**LBNE-LANND**
- Modular structure of $5^3$ m$^3$ cubes
- Evacuable
- Charge readout in single-phase LAr

**LBNE-LAr40**
- 2x20 kton
- 3.7 m horizontal drift
- Not evacuable, membrane tank
- Charge readout in single-phase LAr

**GLACIER, 100 kton**
- 20 m vertical drift
- Not evacuable
- Charge readout in double-phase LAr with amplification

**Scaled from Icarus-T600 by 2.66$^3$**
- Not evacuable
- Charge readout in single-phase LAr

**Perlite insulation**
- Low conductivity foam glass light bricks for the bottom support layer

References:
- D. Angeli et al., JINST 4 (2009) P02003
- D. B. Cline, F. Raffaelli, F. Sergiampietri, JINST 1 T09001 2006
- A. Rubbia hep-ph/0402110
- Venice, Nov 2003
- JINST 1 T09001 2006
## Comparison Water - liquid Argon

<table>
<thead>
<tr>
<th>Particle</th>
<th>Cerenkov Threshold in H₂O (MeV/c)</th>
<th>Corresponding Range in LAr (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.6</td>
<td>0.07</td>
</tr>
<tr>
<td>μ</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>π</td>
<td>159</td>
<td>16</td>
</tr>
<tr>
<td>K</td>
<td>568</td>
<td>59</td>
</tr>
<tr>
<td>p</td>
<td>1070</td>
<td>105</td>
</tr>
</tbody>
</table>

- LAr allows lower thresholds than Water Cerenkov for most particles
- Comparable performance for low energy electrons
Photodetector R&D

High QE PMTs
Super Bi-Alkali/Ultra Bi-Alkali

- **Ultra BiAlkali:** R7600-200
- **SBA:** R7600-100
- **STD:** R7600

Quantum Efficiency (%)

<table>
<thead>
<tr>
<th>WAVELENGTH (nm)</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency (%)</td>
<td>50</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Hybrid Avalanche Photo-Detector (HPD)

- Electron multiplication by gaseous avalanche
- Single photoelectron sensitivity
- Position resolution
- Possibly large area

Better single photon time, energy and collection efficiency than PMTs

Towards large flat-panel photosensors?

Gas photo-multiplier (GPM)

- Electron multiplication by gaseous avalanche
- Single photoelectron sensitivity
- Position resolution
- Possibly large area
Technical issues for large LAr TPCs

- High Voltage systems
- Long Drift
- Diffusion
- Argon Purity
- Readout devices and electronics
- LAr vessel
- Detector engineering, safety, underground construction
- Argon Purification Cryogenic pumps
LAr R&D

Standard LNG tank

Membrane LNG tank

BNL development of cold electronics

FNAL LAr Purity Demonstrator

ArDM

Cockroft-Walton generator

ICARUS signal feedthrough flange

ArgonTube, 5 m drift
Charge readout in double phase LAr

A. Badertscher et al., NIM A641 (2011) 48

Cu strips (x&y)
Kapton layer
PCB

2D anode
LEM

3 mm readout pitch
1 mm thick FR4 500 μm holes

Also tests with Micromegas (Saclay group)

Effective charge gain of ≈27

2 light readout

xView event display (event 1898)
yView event display (event 1898)
World-wide effort on event reconstruction in LAr I

**ICARUS 50 L @ CERN**

Proton identification in ν interactions

**ICARUS 600 ton @ LNGS**

Fully reconstructed event

C. Rubbia et al., arXiv:1106.0975 [hep-ex]

World-wide effort on event reconstruction in LAr II

ArgoNeut 175 L @ FNAL

Data in black, MC in red

Cos(\(\theta_\mu\))

\[
\begin{array}{c|c|c}
\text{Mean} & \text{RMS} & \text{Integral} \\
0.9295 & 0.0750 & 713.6 \\
\end{array}
\]

\(p_\mu\) (GeV/c)

\[
\begin{array}{c|c|c}
\text{Mean} & \text{RMS} & \text{Integral} \\
3.437 & 3.72 & 796 \\
\end{array}
\]

νμ CC events

C. Bromberg, GLA2011
World-wide effort on event reconstruction in LAr III

250 L @ J-PARC

Tagged low-momentum Kaon test beam

Prototype setup with 1 cm readout pitch operated in single-phase LAr

Bethe-Bloch for proton, kaon, pion
R&D on a magnetized LAr

- superconducting solenoid immersed in LAr
  - LHe or HTS superconductor?
- B parallel to E
- low field (B=0.1 T) to measure μ charge
- strong field (B=1 T) to measure ‘e’ charge
- now part of WP4 Laguna-LBNO managed by CERN

Comparison of superconducting solenoidal magnets. ATLAS column corresponds to the solenoid.

<table>
<thead>
<tr>
<th>Magnetic induction (T)</th>
<th>10 kton LAr</th>
<th>100 kton LAr</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1/0.4/1.0</td>
<td>0.1/0.4/1.0</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Solenoid diameter (m)</td>
<td>30</td>
<td>70</td>
<td>2.4</td>
<td>6</td>
</tr>
<tr>
<td>Solenoid length (m)</td>
<td>10</td>
<td>20</td>
<td>5.3</td>
<td>12.5</td>
</tr>
<tr>
<td>Magnetic volume (m³)</td>
<td>7700</td>
<td>77000</td>
<td>21</td>
<td>400</td>
</tr>
<tr>
<td>Stored magnetic energy (GJ)</td>
<td>0.03/0.5/3</td>
<td>0.3/5/30</td>
<td>0.04</td>
<td>2.7</td>
</tr>
</tbody>
</table>

First operation of a LAr TPC in a magnetic field @ ETHZ

NIM A 555 (2005) 294
Some concluding thoughts

- **Maximize physics output of next generation large neutrino detectors**
  - sensitivity to different channels and extended energy range, possibly down to ~10 MeV
  - magnetization is an essential requirement if on a neutrino factory beam

- **Synergy between precise detectors for long baseline neutrino experiments, proton decay and astrophysical neutrinos**
  - Water Cherenkov and LAr TPCs detectors are appealing options for superbeam (and β beam) ν sources, with excellent sensitivity to proton decay and astrophysical ν sources
  - underground location (> 500 m.w.e.) is a must

- **Reduced systematics of a ν factory beam** offers unique sensitivity for short baseline physics (cross sections, high Δm² oscillations)
  - mini-NuFactory with lower energy and intensity?

- **R&D on photodetectors** is important for all considered technologies
  - also for LAr TPCs, since LAr is a very good scintillator
...detector specific

- **TASD segmented detectors** are interesting options as near detectors
  - can they identify $\tau$’s?
  - if considered for large far detectors, sensitivity to astrophysical sources, proton decay (?) must be studied and an underground siting must be considered

- **Proposals for up to 1 Mton Water Cherenkov detectors**

- **World-wide effort on LAr technology**
  - 600 ton ICARUS detector operating at LNGS
  - R&D on double-phase LAr-TPC, cold electronics, long drifts, purification, HV systems
  - ongoing studies for LAr vessels in underground conditions
  - R&D on LAr detector magnetization
  - exposure of small LAr setups (0.2 – 10 ton) on intense $\nu$ beams or low energy particle test beams already accomplished, ongoing or planned
  - extensive efforts on automated event reconstruction in LAr
  - 170 ton MicroBoone detector approved at FNAL to run on the Booster $\nu$ beam
  - kton-scale LAr prototype seen as necessary step towards 50-100 kton detectors

- **... towards realistic proposals for large LAr TPC**
Backup
MINOS Detector Planes

Detector module with 20 scintillator strips

Assembled plane ready to be lifted
MINOS Detector Readout

MUX boxes route 8 (1 in Near Detector) fibers to one MAPMT pixel
Super-Kamiokande detector

Multi-purpose observatory:
Neutrinos from Sun, atmosphere, supernova, relic SN's, astrophysical point sources, and beams from K2K and T2K
Also: search for nucleon decay, WIMPS, other exotic particles

50 kton water Cherenkov
22.5 kton fiducial volume
(~ 2m away from wall)

2700 m.w.e overburden
cosmic ray BG ~3 Hz

~10 Solar $\nu$/day
~10 Atmospheric $\nu$/day

Inner detector (ID):
~11,100 50 cm PMTs
~2ns timing resolution
~4.5MeV threshold

Outer detector (OD):
water layer ~2m thick,
1,885 20 cm PMTs
History of Super-Kamiokande


SK-I (Rebuild) SK-II (Rebuild) SK-III SK-IV

11146 ID PMTs (40% coverage)
5182 ID PMTs (19% coverage)
11129 ID PMTs (40% coverage)
Electronics Upgrade

Threshold:
(Total energy)
(~4.5 MeV)

(Kinetic energy)
(~4.5 MeV)

5.0 MeV
7.0 MeV
5.0 MeV
<~3.5 MeV

~4.5 MeV <~4.0 MeV
~4.0 MeV

Goal Now
Water Cherenkov: e/μ identification

- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.

- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.

Figures from M. Earl's PhD Thesis

Figures from http://hep.bu.edu/~superk/atmnu/
Reconstruction performance

$p \rightarrow e^+ + \pi^0$ MC (free proton only)

**Resolution (68%)**
- SK-I: 18.1 cm
- SK-II: 20.1 cm

<table>
<thead>
<tr>
<th>mode</th>
<th>Period (coverage)</th>
<th>Detection efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ + \pi^0$</td>
<td>SK-I (40%)</td>
<td>44.6%</td>
</tr>
<tr>
<td></td>
<td>SK-II (19%)</td>
<td>43.5%</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ + \pi^0$</td>
<td>SK-I (40%)</td>
<td>35.5%</td>
</tr>
<tr>
<td></td>
<td>SK-II (19%)</td>
<td>34.7%</td>
</tr>
</tbody>
</table>

Reconstruction performance is not degraded much for $p \rightarrow e^+ (\mu^+) + \pi^0$ modes.

Excellent efficiency even with half PMT density
Liquid Argon Time Projection Chamber

C. Rubbia,
CERN Report 77-8
May 1977

Preamplifier -> Shaping Amplifier -> FADC -> Memory Buffer

Induced current

Induced charge

Charge = area

T=0
The ICARUS steps


1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

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

2001: 300 ton detector tested on surface in Pavia. 600 ton detector operational at LNGS.

NIM A 527 (2004) 329
ICARUS

LAr Cryostat (half-module)

View of the inner detector

HV feedthrough

Field shaping electrodes

300 tons

4 m

4 m

20 m

Wires of the TPC

Drift Length (1.5 m)

UV PMT

Cathode

Wire Chamber Structure

Field Shaping Electrodes (during installation)
Ionization charge readout techniques in LAr

single LAr phase, wire planes

C. Rubbia, CERN Report 77-8, May 1977

double phase Ar
Large Electron Multiplier (THGEM)

- Free $e^-$ drift in LAr towards liquid-vapour interface.
- $e^-$ are extracted to the vapour via extraction grids ($E_{\text{liq}} > 2.5$ kV/cm).
- $e^-$ undergo multiplication in double stage LEM.
- Multiplied charge induces signals on the segmented electrodes of top LEM and anode.

A. Badertscher et al., arXiv:0811.3384
GLACIER Roadmap

@ CERN
small test setups for readout devices, electronics

250 lt @ KEK
low energy K test beam @ J-PARC

ArgonTube@ Bern
5 m drift, 0.4 ton under assembly

to be proposed for test beams in NA @ CERN

6 m³ @ CERN

1 ton LAr, Cockroft-Walton, LAr recirculation and purification, industrial electronics, safety, optimized for dark matter searches, in operation

1-5 kton
full engineering demonstrator for larger detectors + physics