towards a Large Liquid Argon TPC for the NuMI Off-axis Beam

Evolving Political Situation for LAr in U.S: NuSAG Charge:
Oddone Talk:

Evolving Proton Flux Situation: Current
Proton Plan (x 2),
Proton Plan plus using Collider Resources (x 1.5)
Proton Driver mention

Evolving Experiment Situation: Growing official support at Fermilab
(aimed at engineering for 15kt - 50 kt)
Support at Universities..
Forming a collaboration.

Emphasize that technical concept and any possibility that such a detector may be feasible owes a huge (and continuing) debt to ICARUS program.
Large Liquid Argon TPC for the NuMI Off-axis Beam is part of NuSAG charge
We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.

Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

Large Liquid Argon TPC for the NuMI Off-axis Beam is part of a plan at FNAL
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Evolution of Beam Intensities and Rates to NuMI

Main Injector protons/cycle

- 6E13 to NuMI (0.7 Hz)
- 5E13 to NuMI + 1E13 to pbar (0.45 Hz)
- 2.5E13 to NuMI + 1E13 to pbar (0.45 Hz)

NuMI flux to MINOS ~ 2 x 10^{20} protons/year (now)

`Proton Plan' (remove existing limitations) gives NuMI

~ 4 x 10^{20} protons/year before collider turn-off in 2009
~ 6 x 10^{20} protons/year after collider turn-off in 2009

Proton Driver (new Linac) ~ 25 x 10^{20} - whenever PD exists
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Present Concept: Tank, Argon, Electrodes, Readout.

Monte-Carlo studies (efficiency ~ 80% in active/fiducial region)

Issues to/under study:

- Initial `purification' of Argon (dealing with air in Tank)
- Effects of materials used on electron drift lifetime
- Electrode mechanics
- Signal processing (from wire up to DAQ)
- Data Acquisition (from spill based to always live)
- Simulations
- Automated reconstruction (rejection of cosmic rays, event identification)

urls: http://www-off-axis.fnal.gov/flare/ &
http://www-off-axis.fnal.gov/notes/notes.html
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Aim is to produce a viable design for a 15 kt - 50 kt liquid argon detector.
Basic concept follows ICARUS: viz
TPC, drift ionization electrons to 3 sets of wires (2 induction, 1 collection)
record signals on all wires with continuous waveform digitizing electronics

Differences aimed at making a multi-kton detector feasible;
Construction of detector tank using industrial LNG tank as basic structure
Long(er) signal wires
Single device (not modular)

Basic parameters:
Drift distance - 3 meters; Drift field - 500 V/cm (gives $v_{\text{drift}} = 1.5$ m/ms)
Wire planes - 3 (+/-30° and vertical); wire spacing 5 mm; plane spacing 5 mm
Number of signal channels ~ 100,000 (15kt), 220,000 (50kt)
$L_{\text{Radiation}} = 14$ cm, $dE/dx = 2.1$ MeV/cm, 55,000 electrons/cm liberated
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Some Specific challenges:

Argon: (long drift)
- purification - starting from atmosphere (cannot evacuate detector tank)
  - effect of tank walls & non-clean-room assembly process

Wire-planes:
- long wires - mechanical robustness, tensioning, assembly, breakage/failure

Signal processing:
- electronics - noise due to long wire and connection cables (large capacitance)
- surface detector - data-rates,
  - automated cosmic ray rejection
  - automated event recognition and reconstruction

(and there are others  for example, High Voltage)
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Detector Tank based on Industrial Liquified Natural Gas (LNG) storage tanks

Many large LNG tanks in service. excellent safety record; last failure in 1940; reason understood (wrong type of steel)
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3D `Model' cutaway
15 kt detector

Changes from standard LNG tank:
- Inner tank wall thickness increased
- LAr is 2 x density of LNG;
- Trusses in inner tank to take load of the wires;
- Penetrations for signals from inner tank to floor supported from roof of outer tank;
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side view: showing trusses & signal chimneys: only wires reaching the top (solid lines) are read out.
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Beam's eye view showing the electrodes (cathode, field-cage and wires)
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Site Layout (very) Schematic - showing some of the services needed
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Thermodynamics of Liquid Argon in Ideal Tank

Liquid flow

From finite element model results, the convection flow has a maximum velocity of ~8.5 cm/s; the temperature in the tank is quite uniform, with a maximum temperature difference of 0.04 K.

Temperature
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Schematic of Cryogenics for Liquid Argon

LN\textsubscript{2} condenser pipes are inside the Argon tank. The LN\textsubscript{2} pressure sets the temperature of the LAr. Evaporation of LAr occurs at LAr surface; LAr then condenses on and `rains' off the LN\textsubscript{2} pipe.

Heat loads have been estimated:
- LN\textsubscript{2} Usage ~ 35 tons/day
  (cf CHL liquifier at FNAL 100 tons/day)
- 12 trucks or 5 railcars per week
- LN\textsubscript{2} cost at Fermilab $62/ton
  (2002 budget price for 100 ton/day liquefier $2.9 million)
- Tank loses ~ 25 tons argon/day without cooling
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Liquid Argon `purity' requirements

\[ \text{Signal size vs `purity' for different drift distances} \]

\[ \text{Desired Signal Level (22,500 e)} \]

\[ \text{Noise level (2500 e)} \]

\[ \text{\textquotedblleft purity\textquoteright \ in parts per trillion (ppt) O}_2 \text{ eq.} \]

\[ \begin{align*}
\text{1 ms} & \quad \text{drift} \rightarrow \text{10 ms lifetime} = 30 \text{ ppt} \\
\text{2 ms} & \quad \text{drift} \rightarrow \text{6 ms lifetime} = 50 \text{ ppt} \\
\text{3 ms} & \quad \text{drift} \rightarrow \text{3 ms lifetime} = 90 \text{ ppt}
\end{align*} \]

\[ \text{ICARUS achieved 10 ms in 1997} \]
\[ \text{T600 lifetime evolution implies >10 ms asymptotic value} \]

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NuFact05, Liquid Argon for NuMI Off-axis beam
towards a Large Liquid Argon TPC for the NuMI Off-axis Beam

Schematic of Argon Delivery and Initial Purification

Reject car

Initial QA

Filters

Intermediate Storage Tanks

High purity detector tank

High purity lines (1 ppm)

Ultra-high purity lines (0.1 ppb)
Evolution of Argon purity during the tank-filling process

Phase I: initial purge - 100-200 tons of LAr (~ 2 weeks) (vessel purged but not evacuated)
- rapid volume exchange => rapid purification
- Main issue: large oxygen capacity required
Milestone: achieve 10 ms lifetime before continuing the fill process

Phase II: filling
- Purity level determined by balance of the filtering vs. impurities introduced with the new argon - assume circulation of 30 tons/hour

Phase III: operation
- Low rate of volume exchange (74 days)
- Removal (mainly) of the impurities introduced with new argon
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- In this phase out-gassing of tank walls, cables and other materials becomes a visible factor.
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System at Fermilab PAB for testing filter materials and contaminating effects of detector materials (eg tank-walls, cables)

G. Carugno et al., NIM. A292 (1990)
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A gift from Italy
A key tool of the trade - the purity monitor

UV light flash to photocathode

Cathode (-) Grid (ground) Anode (+)

signal in Gas
PAB data

\[ \frac{Q_a}{Q_c} = \exp\left(-\frac{t}{\tau}\right) \]

\[ V_{\text{drift}} = \frac{L}{t} \]

We will need many of these

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Wire Planes:
Induction (2 +/- 30) and Collection Planes spaced by 5 mm
5mm pitch within planes
~220,000 signal wires total (50 kTon), ~100,000 signal wires (15 kTon)
Longest wire ~35 meters (50 kTon), ~23 meters (15 kTon)

Need to be robust - no breakages
Need practical assembly and installation procedure.

Wire Material 150 micron Stainless

Present Concept: (different from ICARUS)
Tension implemented by attaching a weight to each wire (~1kg) to avoid
tension changes due to temperature changes.
A system of pulleys distributes the weights at the bottom of the tank.

Small horizontal spacers between wires every 2 to 3 meters
along the wires ensure proper spacing between wires and limit amount of free
wire in case of breakage.
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Geometry of wire arrangement at base of tank

(a picture that needs a 1000 words?)
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Electronics and Data Acquisition Summary

Electronics:
ICARUS scheme - an intelligent waveform recorder on each wire:
Amplifier sensitivity achieved in existing custom devices for this capacitance
\[(S/N) = \frac{22,000 \text{ e}}{2500 \text{ e}} = 8.5/1\]
- digitize with commercial ADCs adequate performance, reasonable cost
- intelligence from commercial FPGAs adequate performance, reasonable cost.

Data Acquisition
Use commercial switches and multiplexors
Have a design to achieve 5 Gbyte/second into 200 PC's for reasonable cost.
Data Acquisition schematic

Raw data rate = \(n_{\text{wires}} \times 2.5 \text{ MHz}\); need 2 bytes per sample

WFT (Wave Form Train) is all the digitizations

`Zero' suppression: Cosmic ray rate is 200 kHz; each ray \(~5000\) signals,
Set intelligent threshold in FPGA, pass next 40 samples

DAT (Data Above Threshold)

Processing each hit fully in FPGA to return pulse-height and time;
requires 4 bytes/hit

FHP (Full Hit Processing)
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### 50 kt data rates

<table>
<thead>
<tr>
<th>Data Type &amp; Data Rates</th>
<th>Spill Only* (bytes/sec)</th>
<th>Always Live (bytes/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Train</td>
<td>$2 \times 10^9$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Data above threshold</td>
<td>$8 \times 10^7$</td>
<td>$4 \times 10^{10}$</td>
</tr>
<tr>
<td>Full hit processing</td>
<td>$8 \times 10^6$</td>
<td>$4 \times 10^9$</td>
</tr>
</tbody>
</table>

Note: Full hit processing allows for Always Live running

* Spill Only looks at 4 milliseconds (to see events plus any early cosmic rays) each spill (every 2 seconds)
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Simulation Results

LArTPC
Total absorption calorimeter
5mm sampling → 28 samples/rad length
Excellent energy resolution

First pass studies using hit level MC show $81 \pm 7\% \nu_e$ efficiency and Neutral Current rejection factor ~70

(only need NC rejection factor of 20 to reduce NC background down to $\frac{1}{2}$ the intrinsic $\nu_e$ rate)
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Electrons compared to $\pi^0$s at 1.5 GeV in LAr TPC

Dot indicates hit, color is collected charge
green=1 mip, red=2 mips (or more)

Electrons
Single track (mip scale)
starting from a single vertex

$\pi^0$
Multiple secondary tracks pointing back to the same primary vertex
Each track is two electrons
- 2 mip scale per hit

use both topology and dE/dx to identify interactions

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Neutral current event with 1 GeV $\pi^0$

$$\nu_\mu + n \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + n$$

$$(1 \text{ GeV}) \pi^0 \rightarrow \gamma + \gamma$$

3.5% $X_0$ samples
in all 3 views

4 cm gap

12% $X_0$ samples
alternating x-y
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Efficiency and Rejection study  Tufts University Group

Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of “signal” events by experts.

Neutrino event generator: NEUGEN3, used by MINOS/NOvA collaboration (and others) Hugh Gallagher (Tufts) is the principal author.

GEANT 3 detector simulation (Hatcher, Para): trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:
50 events each of $\nu_e \text{CC}$, $\nu_\mu \text{CC}$ and NC
  - individual samples to train
  - mixed samples to test training

Blind scan of 450 events
scored from 1-5 with
  - signal=5
  - background=1
**Large Liquid Argon TPC for the NuMI Off-axis Beam**

**Overall efficiencies, rejection factors, and dependencies**

<table>
<thead>
<tr>
<th>Event type</th>
<th>N</th>
<th>pass</th>
<th>eff.</th>
<th>rej.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>290</td>
<td>4</td>
<td>~100%</td>
<td>72.5</td>
</tr>
<tr>
<td>signal $\nu_e$</td>
<td>32</td>
<td>26</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Beam $\nu_e$: CC</td>
<td>24</td>
<td>14</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>8</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam $\nu_e$: CC</td>
<td>13</td>
<td>10</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>19</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Efficiency is substantial even for high multiplicity (DIS) events

Efficiency is $\sim 100\%$ for $y < 0.5$, and $\sim 50\%$ above this

Overall efficiency 81% +/- 7%

Rejection of NC is 73 (+60, -30)
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Sensitivity =
detector mass \times
detector efficiency \times
protons on target/yr \times
# of years
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Initial costing exercise, in Million $, not fully loaded, site preparation not included; costs are estimates from engineers involved.

<table>
<thead>
<tr>
<th>Size</th>
<th>50kton</th>
<th>15kton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30m H x 40 m D</td>
<td>20m H x 26 m D</td>
</tr>
<tr>
<td>Argon cost</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>Cryogenic/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purification plant</td>
<td>6.5</td>
<td>5.0</td>
</tr>
<tr>
<td>HV planes</td>
<td>5.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Wire Chambers</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Electronics</td>
<td>5.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Tank related costs</td>
<td>32.1</td>
<td>20.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96.3</strong></td>
<td><strong>53.9</strong></td>
</tr>
</tbody>
</table>
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R&D efforts underway

~ 8 ft

~ 4 ft

at Yale

at FNAL

UCLA/INFN at CERN

5 m

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From presentation to NuSAG:
R&D path over the next year shaped by open questions for large detectors:

Key Hardware Issues

Technology transfer
- Test setup at FNAL
- Seeing tracks and light production at Yale

Understanding long drifts at UCLA/CERN
Purity tests setups at Fermilab
- Introduction of impurities
- Test of detector and tank materials
- Test of filtering materials
- Purification rate

Very long electrode assembly/stability and readout
Design for detector to be assembled with industrial techniques
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From presentation to NuSAG (cont):

R&D path over the next year shaped by open questions for large detectors: (part2)

Key software, feasibility and infrastructure issues

Continuing Monte Carlo work – automated event reconstruction

Costing study

Growing a strong collaboration
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Schedule:
Tests of materials and filters start in late August;
Presentation of report to NuSAG by mid-August;
White Paper with conceptual design by early Autumn;
Tests and Studies planned for the coming year;

Summary
Have support from Fermilab - engineering and increased funding

Are receiving generous support for technology transfer from experts in Europe and hoping to learn more from ongoing tests there.

Would like to encourage your participation
Back-ups, extras
LArTPC work underway at Yale

How good are these detectors at IDing low (~1 GeV) energy $\nu$ interactions?

- understand the technology
- purity studies
- understand detector response at very low energies
- study combination of charge and light production for particle ID

Constructing small prototype vessel this summer

Work funded by DOE Advanced Detector Research Grant

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everything about drifting in one fine slide

\[ \sigma_D = \sqrt{\frac{2 \cdot \lambda}{v_d}} \]

Longitudinal rms diffusion spread at 0.5 kV/cm
Average \( \langle \sigma_D \rangle = 1.1 \) mm
Maximum \( \sigma_D = 1.6 \) mm

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setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly in PAB at FNAL.
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Expanded view of wire arrangement at base of tank
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general electronics schematic

based on P. Rubinov, Flare Workshop 11/2004

amplifier sensitivity achieved in existing custom devices - probably want ASIC
commercial ADCs adequate performance, reasonable cost
commercial FPGAs adequate performance, reasonable cost
128 channel boards, reasonable size (and cost) 1000 - 2000 such boards
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**Data Acquisition schematic**

*General Scheme using commercial links and switches*

- Front-end Boards (1000 - 2000)
- Ethernet Network
- Processors (for online reconstruction)

(M. Bowden, M. Votava, Flare Workshop 11/2004)
Data Acquisition Schematic

commercial switches well matched to required data rates.

Data Network - per M. Bowden, M. Votava (Flare Workshop 11/2004)

allows for 5 GByte/sec rate into ~ 200 Processors
Phase I: initial purge - 100-200 tons of LAr (~ 2 weeks) (vessel purged but not evacuated)
- rapid volume exchange => rapid purification
- Main issue: large oxygen capacity required

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Liquid Argon `purity' requirements

Signal size vs `purity' for different drift distances

`purity'/lifetime requirements for <20% signal loss
3m drift -> 10 ms lifetime = 30 ppt
2m drift -> 6 ms lifetime = 50 ppt
1m drift -> 3ms lifetime = 90 ppt

ICARUS achieved 10 ms in 1997
T600 lifetime evolution implies >10 ms asymptotic value