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.

U.S. Department of Energy
and the
National Science Foundation

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<u>Charge 3</u>

We request that NuSAG address the APS Study's suggestion that the U.S. participate in *"A timely accelerator experiment with comparable* $sin^2 2\theta_{13}$ *sensitivity [to the recommended reactor experiment, i.e.* $sin^2 2\theta_{13}=0.01$*]* and sensitivity to the mass-hierarchy through matter effects."

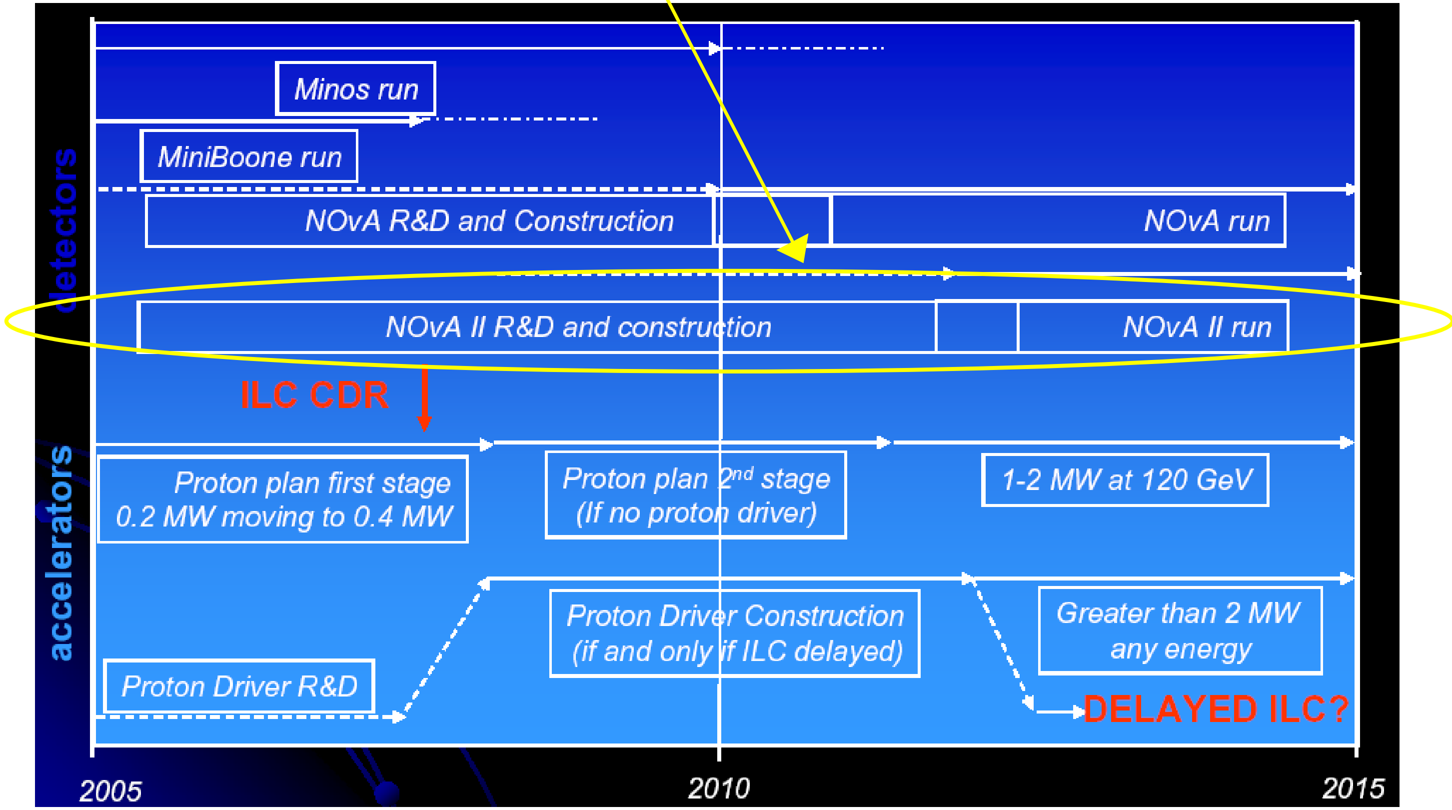
The options to be considered should include, but not be limited to:

- U.S. participation in the T2K experiment in Japan
- Construction of a new off-axis detector to exploit the existing NUMI beamline from Fermilab to Soudan, as proposed by the Nova collaboration
- As above but using a large liquid argon detector.

Large Liquid Argon TPC for the NuMI Off-axis Beam is part of NuSAG charge

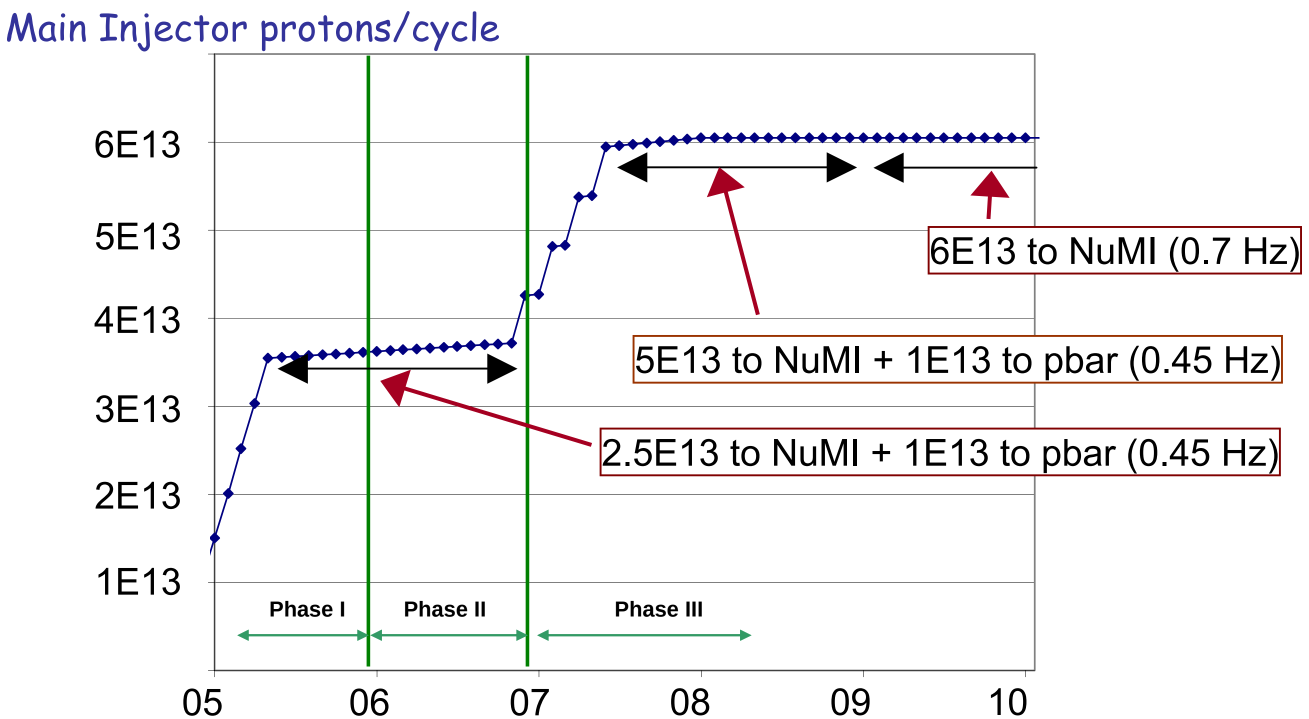
- We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.
- Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

P. Oddone to EPP2010, May 2005



Large Liquid Argon TPC for the NuMI Off-axis Beam is part of a plan at FNAL

Evolution of Beam Intensities and Rates to NuMI



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

`Proton Plan' (remove existing limitations) gives NuMI

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

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

Proton Driver (new Linac) ~ 25×10^{20} - whenever PD exists

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

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

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

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_{drift} = 1.5 m/ms)
- Wire planes - 3 (+/-30^0 and vertical); wire spacing 5 mm; plane spacing 5 mm
- Number of signal channels ~ 100,000 (15kt), 220,000 (50kt)
- $L_{Radiation}$ = 14 cm, dE/dx = 2.1 MeV/cm, 55,000 electrons/cm liberated

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

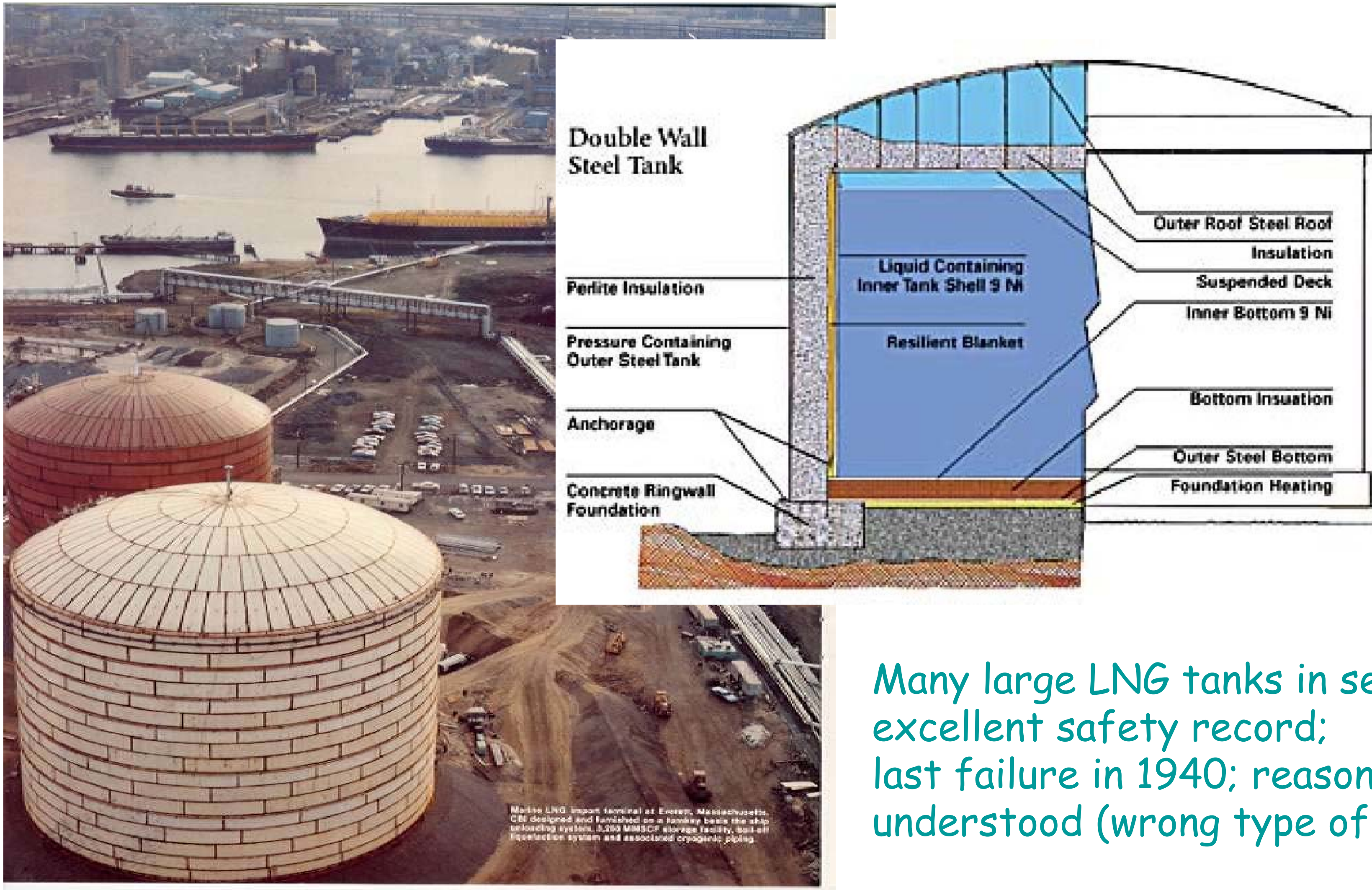
Signal processing:

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)

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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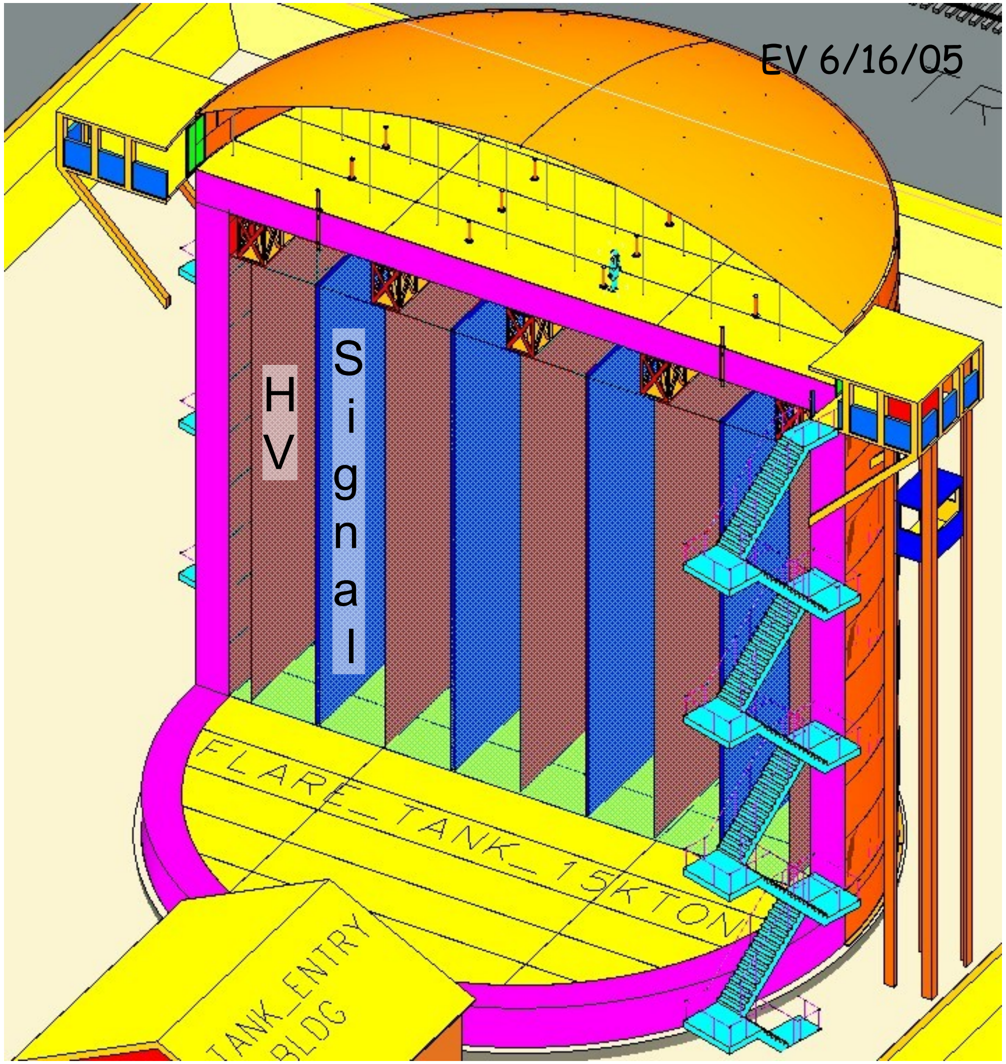

3D `Model' cutaway
15 kt detector

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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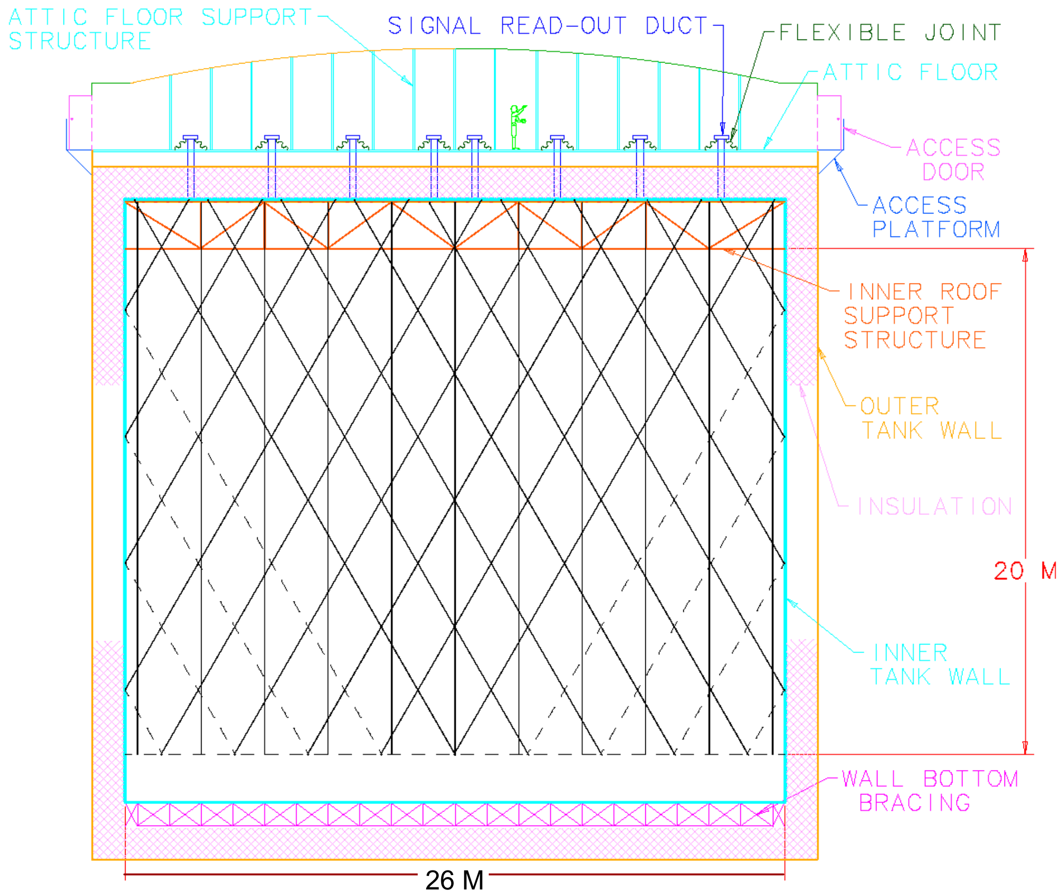

side view: showing trusses & signal chimneys:
only wires reaching the top (solid lines) are read out.

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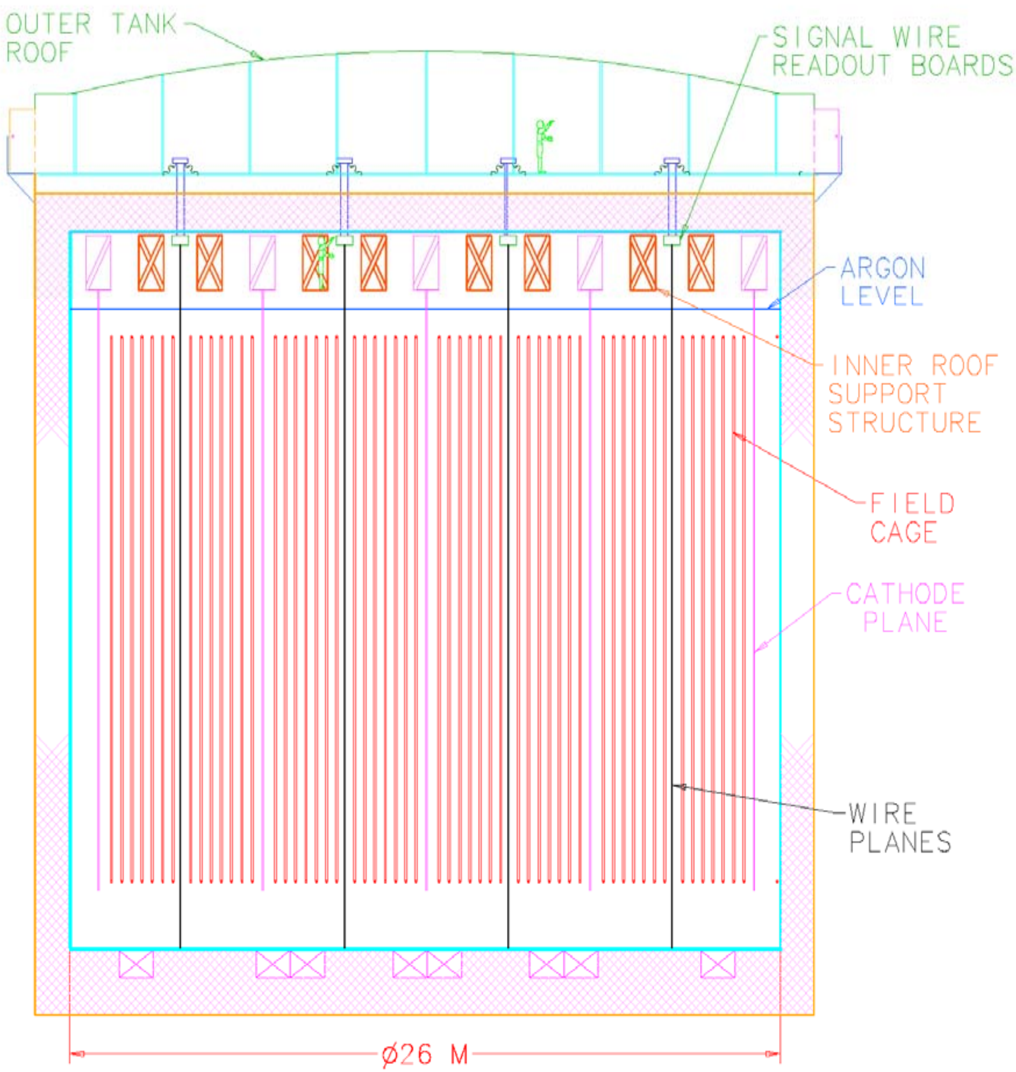

Beam's eye view showing the electrodes (cathode, field-cage and wires)

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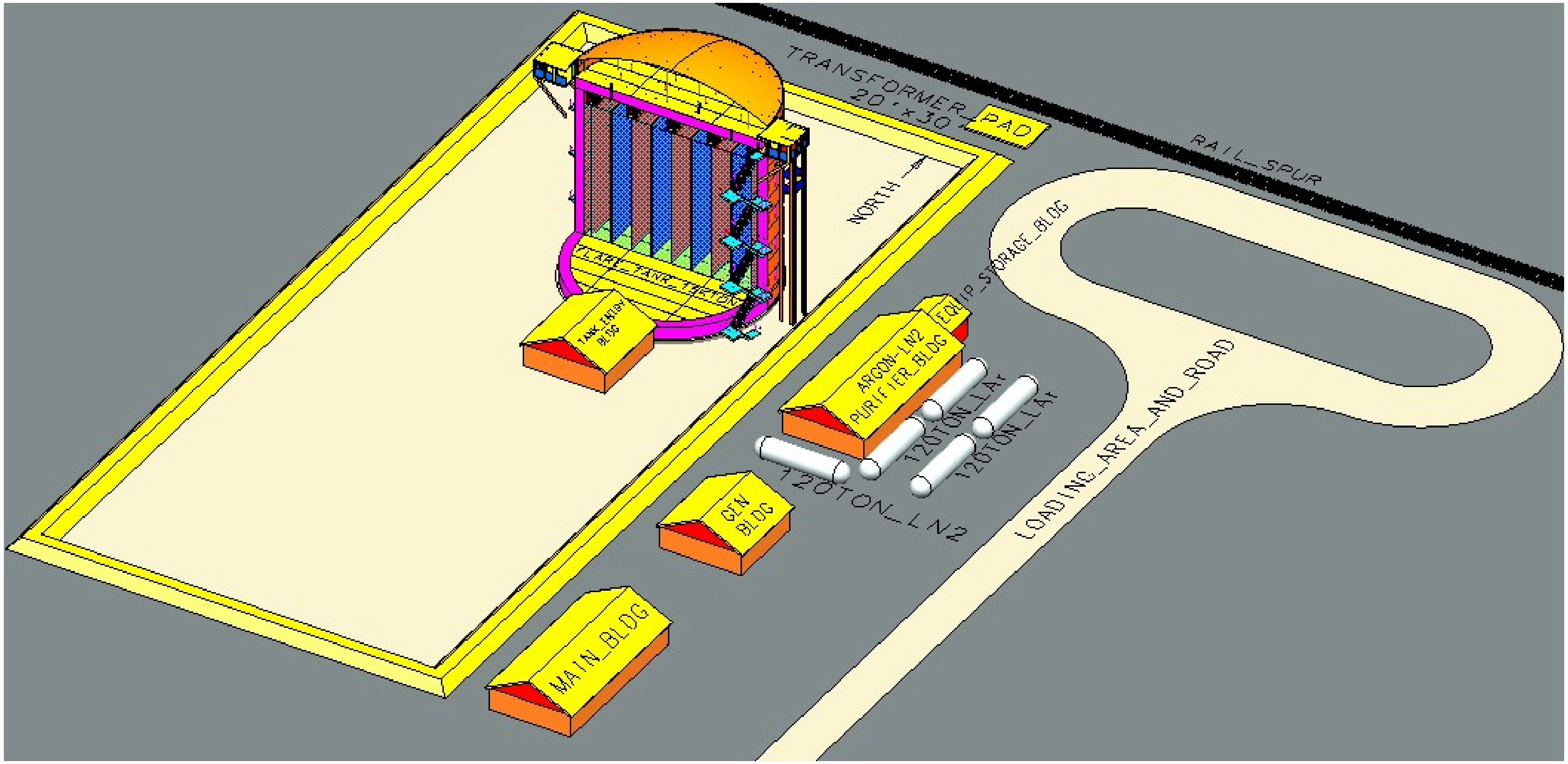
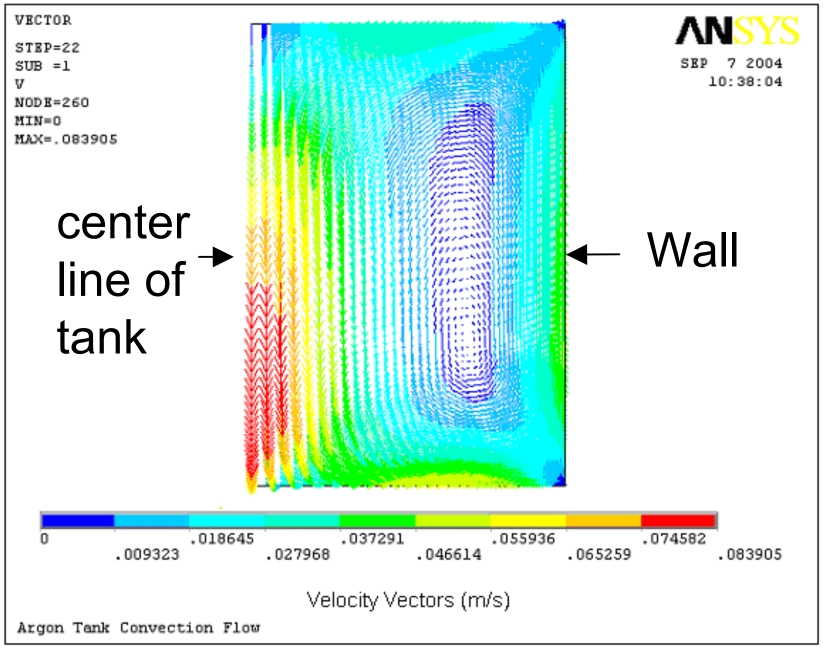
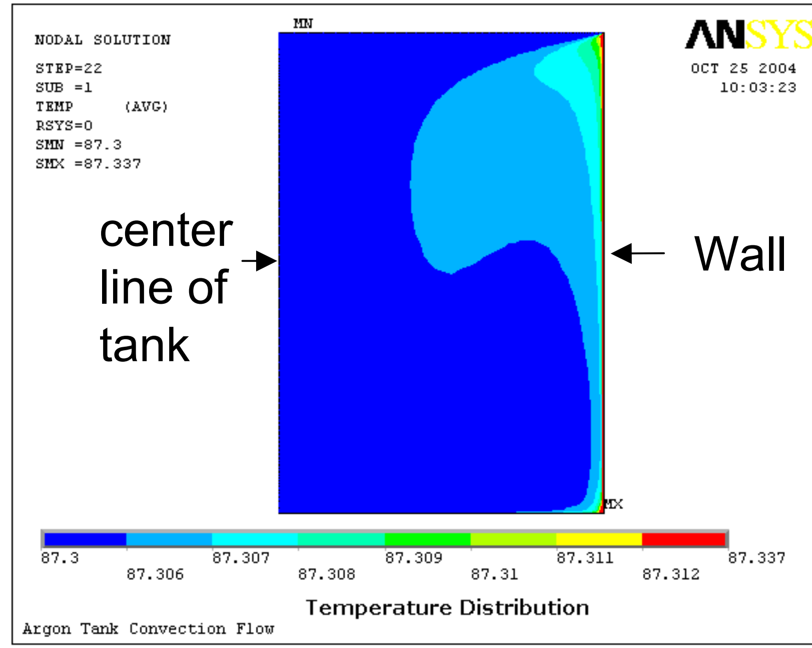


Site Layout (very) Schematic - showing some of the services needed

Thermodynamics of Liquid Argon in Ideal tank



Liquid flow

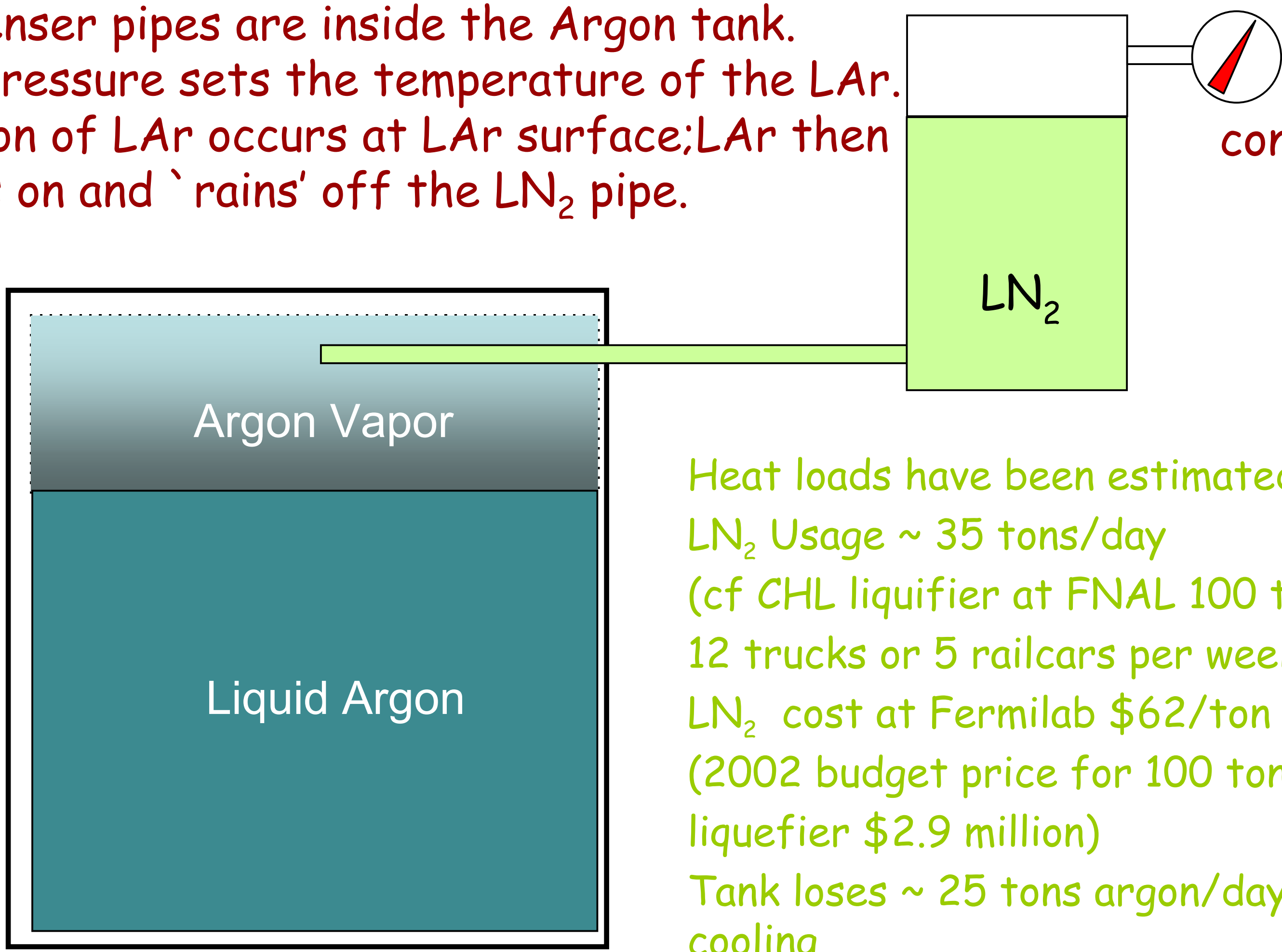


Temperature

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.

Schematic of Cryogenics for Liquid Argon

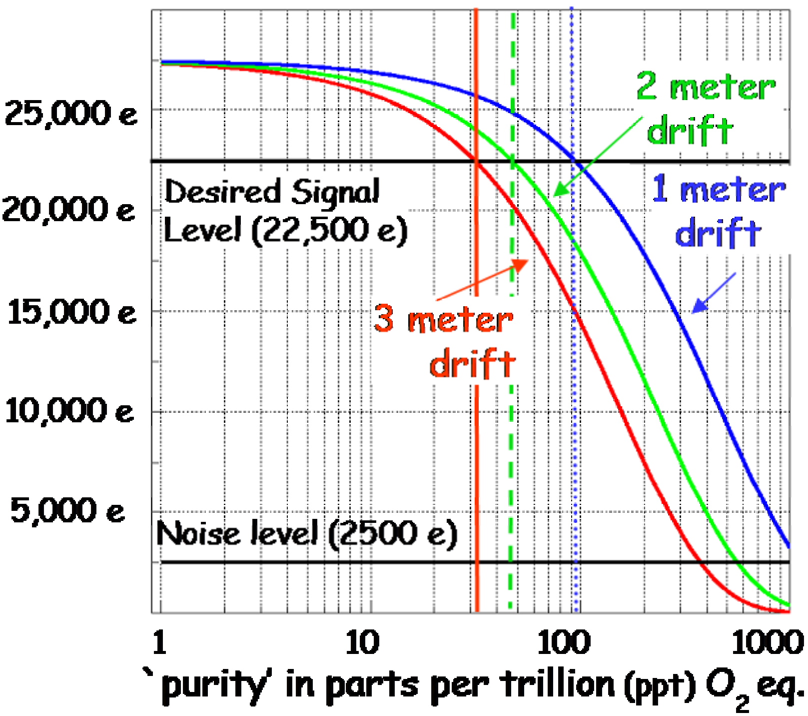
LN_2 condenser pipes are inside the Argon tank.
The LN_2 pressure sets the temperature of the LAr.
Evaporation of LAr occurs at LAr surface;LAr then condenses on and `rains' off the LN_2 pipe.



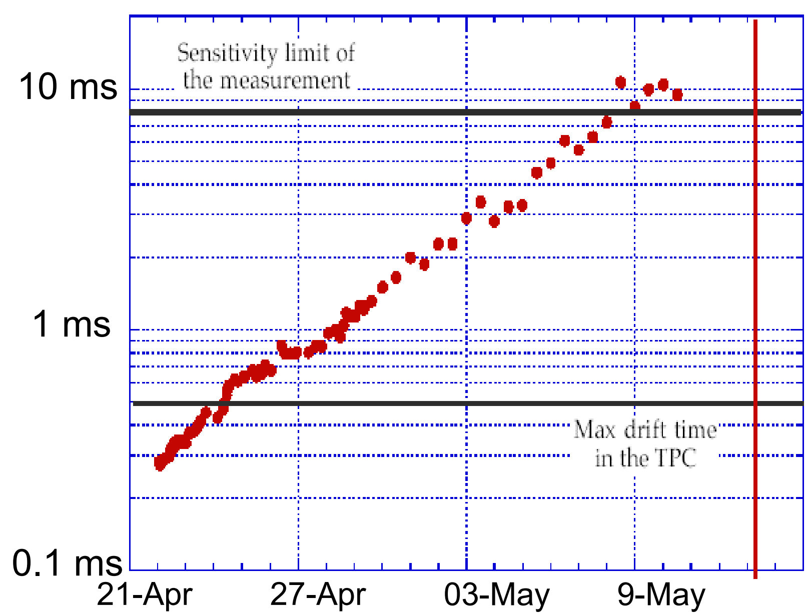
Heat loads have been estimated:
LN_2 Usage ~ 35 tons/day
(cf CHL liquifier at FNAL 100 tons/day)
12 trucks or 5 railcars per week
LN_2 cost at Fermilab $62/ton
(2002 budget price for 100 ton/day liquefier $2.9 million)
Tank loses ~ 25 tons argon/day without cooling

Liquid Argon `purity' requirements

Signal size vs `purity' for different drift distances



data from ICARUS T10 1997

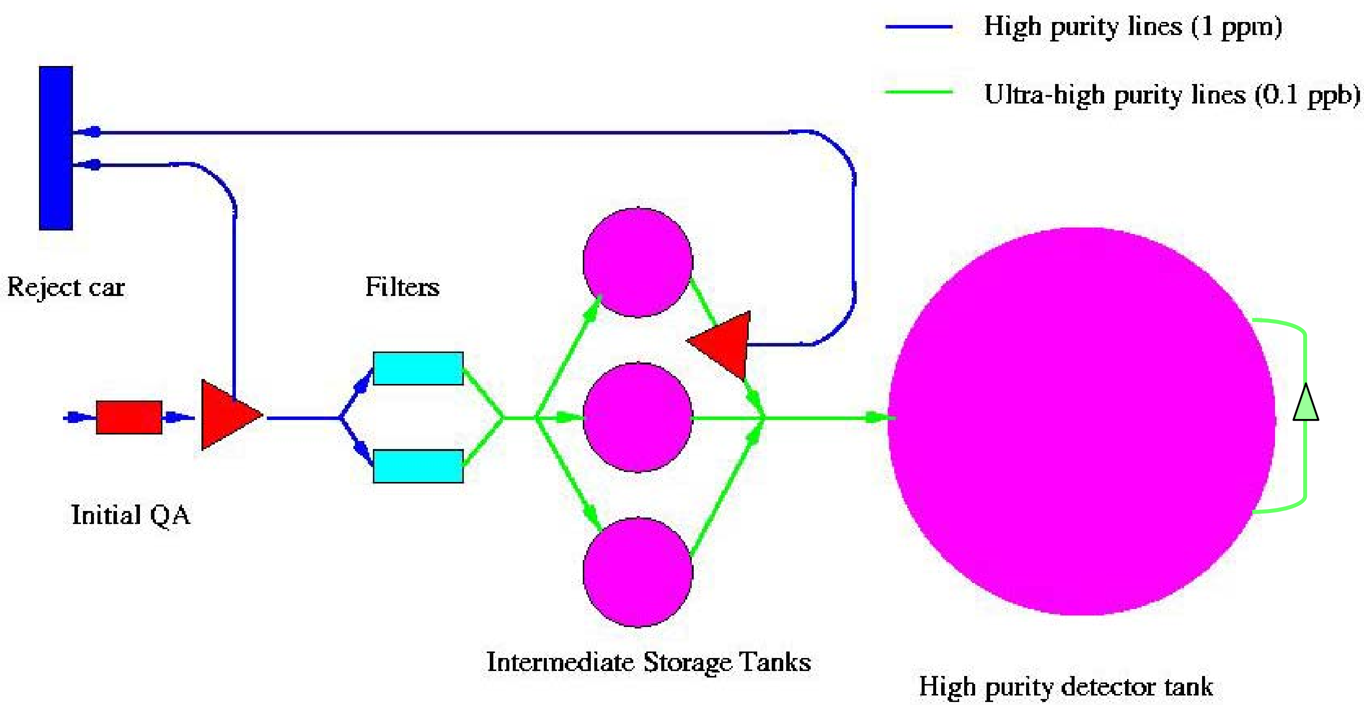


`purity'/lifetime requirements for <20% signal loss

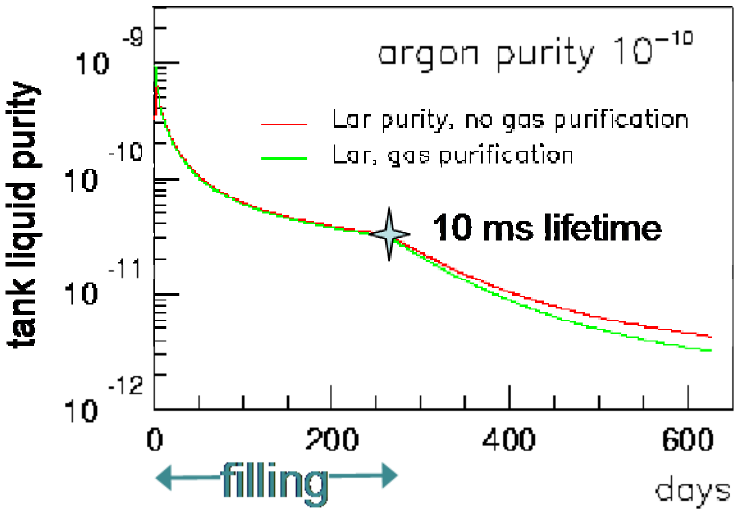
- 3m drift -> 10 ms lifetime = 30 ppt
- 2m drift -> 6 ms lifetime = 50 ppt
- 1m drift -> 3ms lifetime = 90 ppt

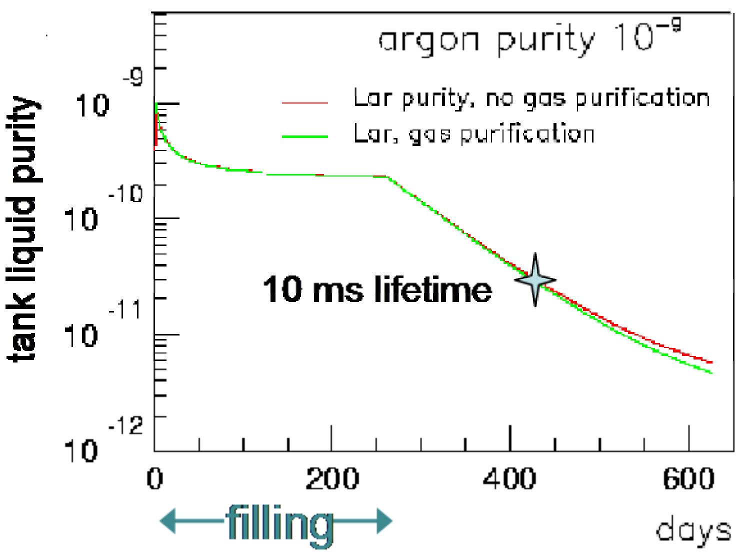
ICARUS achieved 10 ms in 1997
T600 lifetime evolution implies
>10 ms asymptotic value

Schematic of Argon Delivery and Initial Purification



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

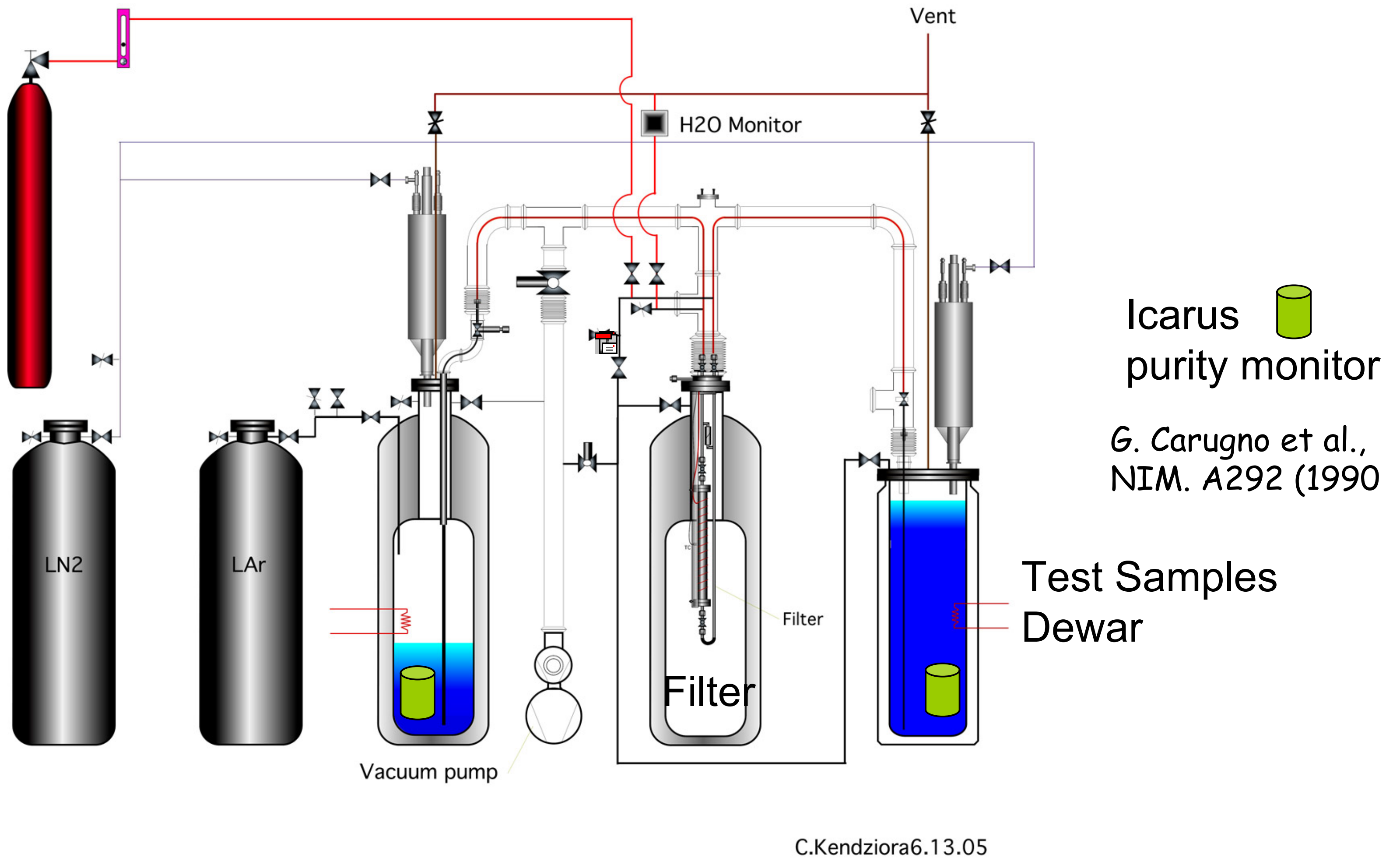
Phase II: filling

- 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
- Balance between purification and out-gassing
- In this phase out-gassing of tank walls, cables and other materials becomes a visible factor.

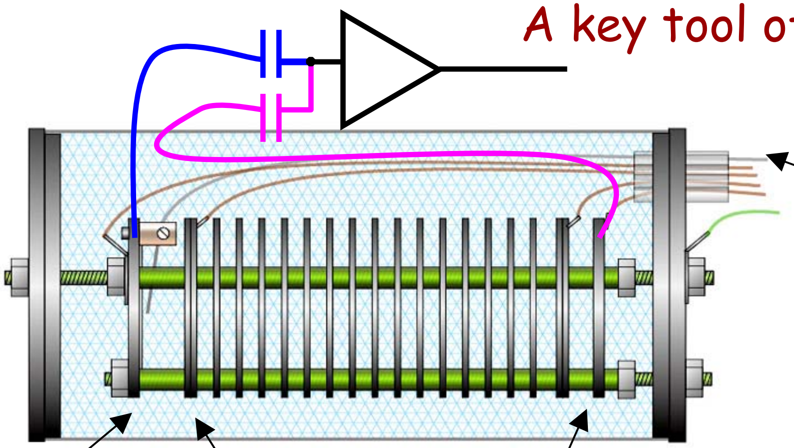
System at Fermilab PAB for testing filter materials and contaminating effects of detector materials (eg tank-walls, cables)



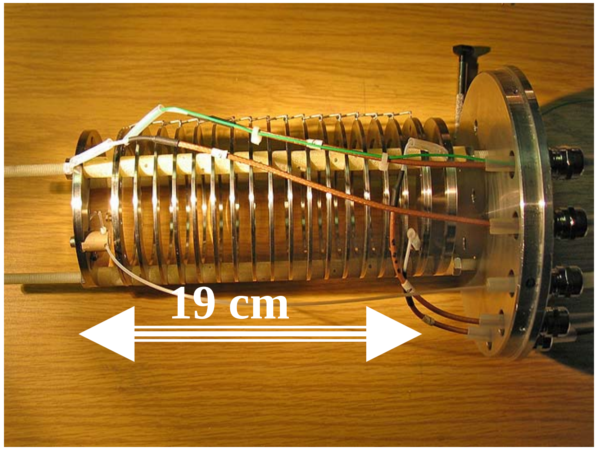
Large Liquid Argon TPC for the NuMI Off-axis Beam

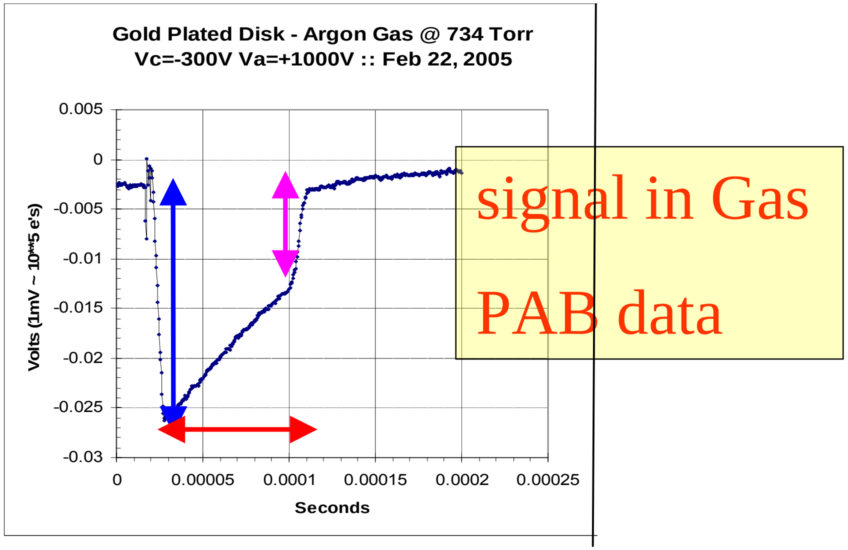
A gift from Italy

A key tool of the trade – the purity monitor



UV light flash to photocathode





$Q_a/Q_c=\exp(-t/\tau)$

$V_{drift} = L / t$

We will need many of these

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)

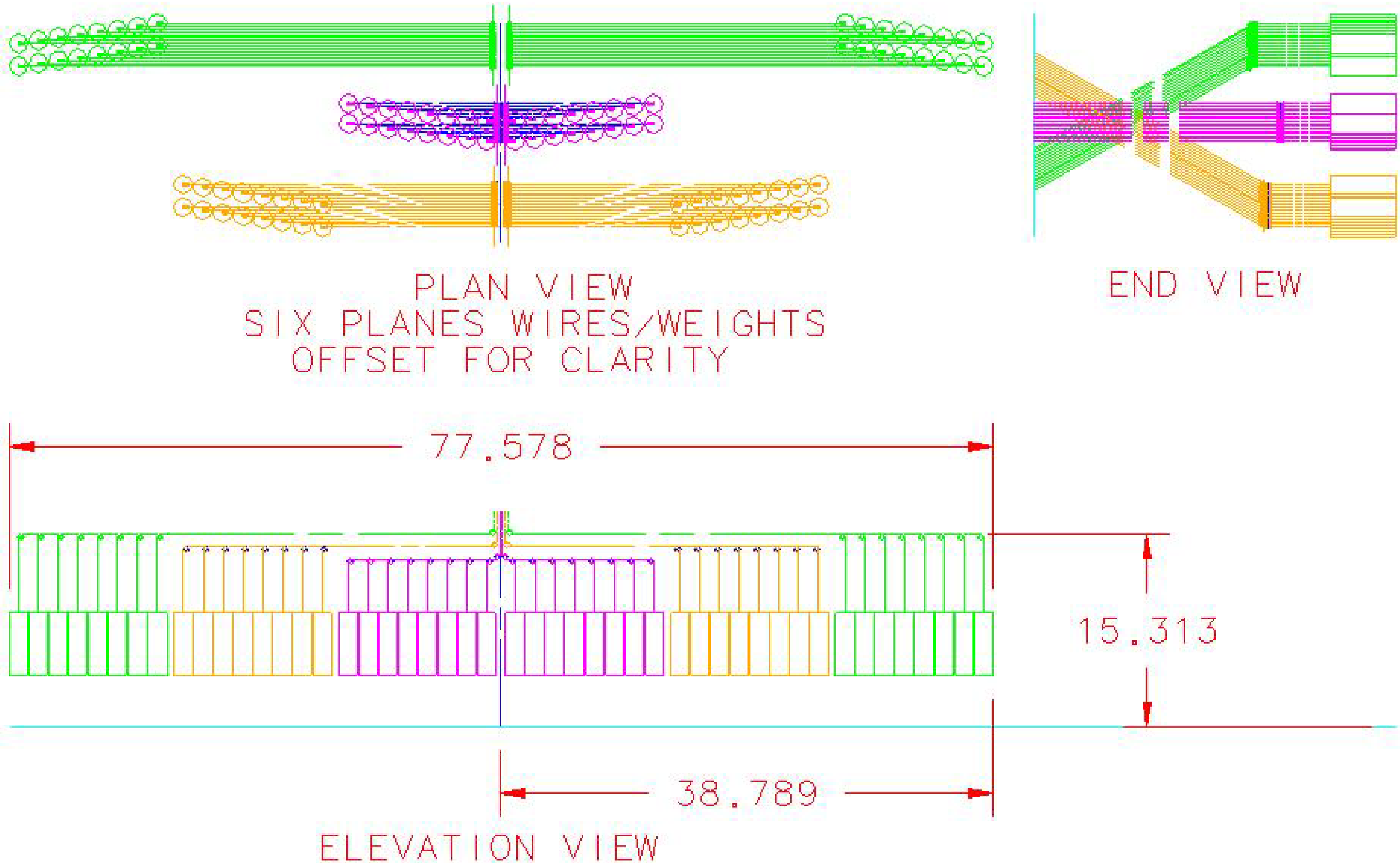
Need to be robust - no breakages
Need practical assembly and installation procedure.

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.

Geometry of wire arrangement at base of tank



(a picture that needs a 1000 words?)

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) =22,000 e / 2500 e = 8.5/1

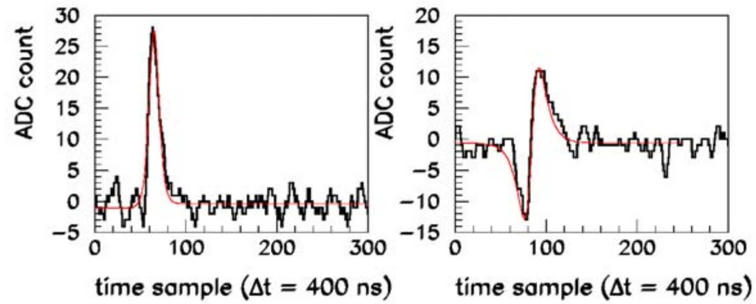
- digitize with commercial ADCs adequate performance, reasonable cost
- intelligence from commercial FPGAs adequate performance, reasonable cost.

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



ICARUS TM/2001-09

Raw data rate = nwires x 2.5 MHz; need 2 bytes per sample

WFT (Wave Form Train) is all the digitizings

`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)

50 kt data rates

Data Type & Data Rates	Spill Only* (bytes/sec)	Always Live (bytes/sec)
Wave Train	2×10^9	~~10^{12}~~
Data above threshold	8×10^7	~~4×10^{10}~~
Full hit processing	8×10^6	4×10^9

exceeds bandwidth of 5 GB/sec

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)

Simulation Results

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

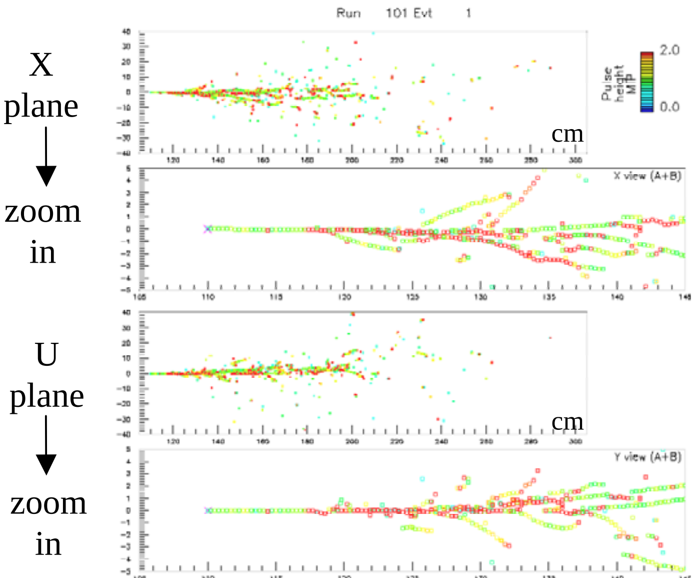
→ high ν_e efficiency
good NC rejection

First pass studies using hit level MC show 81 ± 7 % ν_ε efficiency and Neutral Current rejection factor ~70

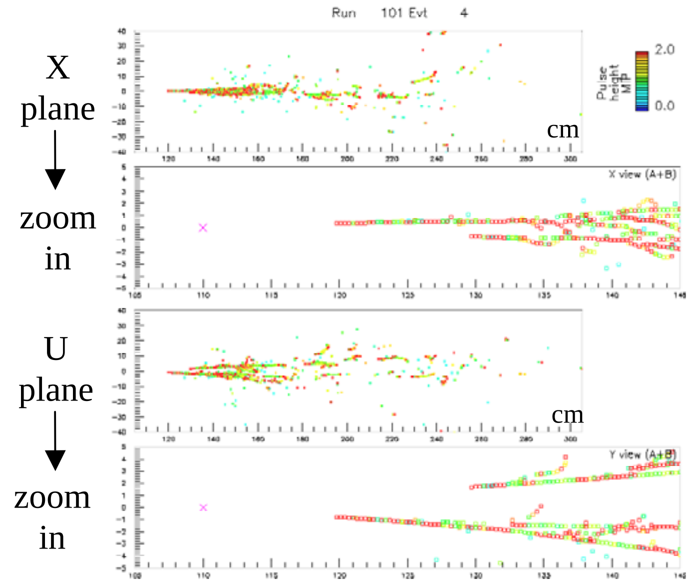
(only need NC rejection factor of 20 to reduce NC background down to ½ the intrinsic ν_ε rate)

Electrons compared to π^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



π^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

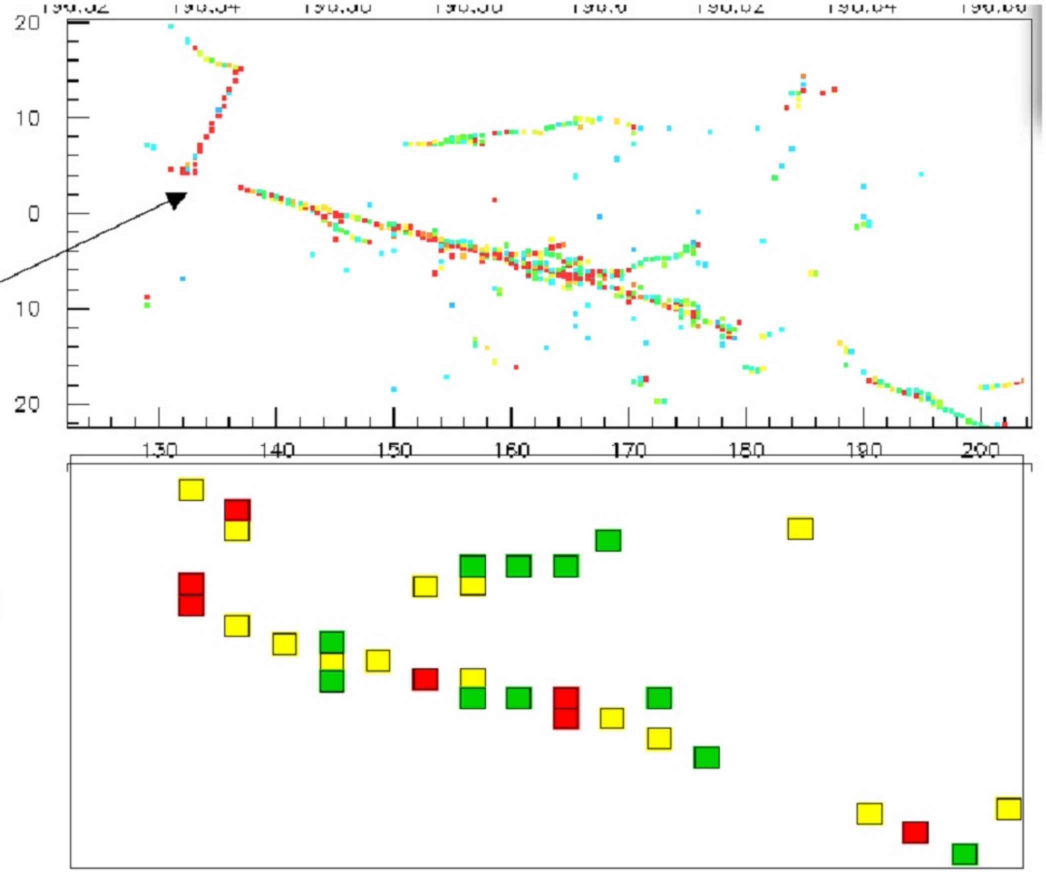
Neutral current event with 1 GeV π^0

$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$
$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

in all 3 views

4 cm gap



12% X_0 samples

alternating x-y

Efficiency and Rejection study   Tufts University Group

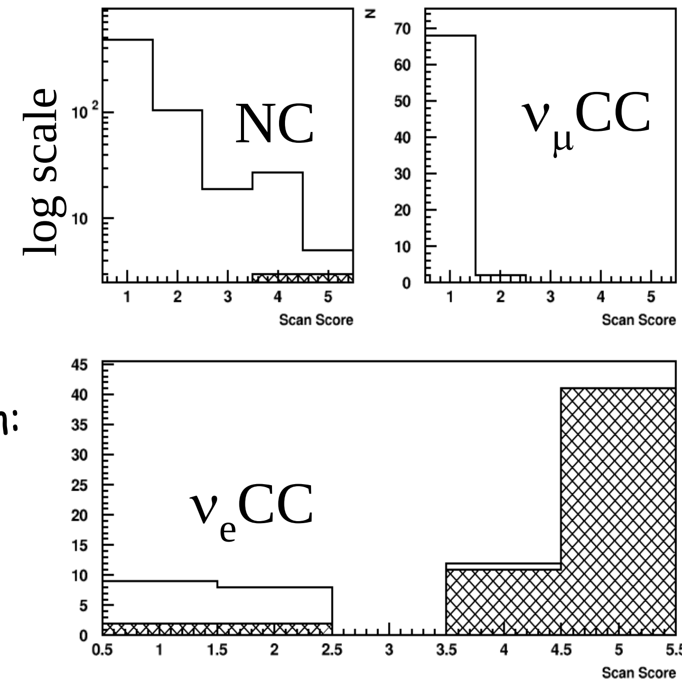
Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of "signal" events by experts.

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 ν_eCC, ν_μCC 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



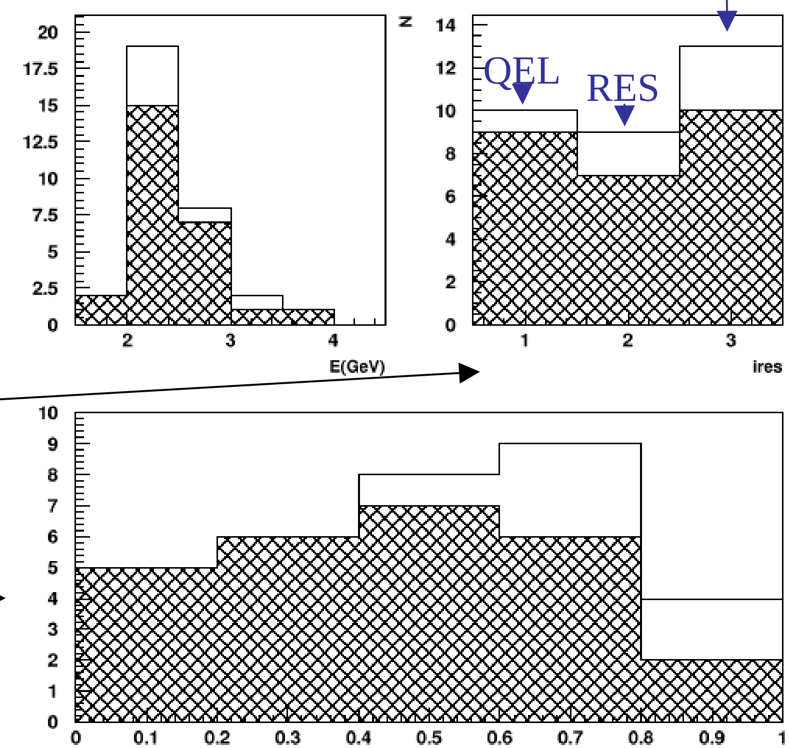
open region: students
hatched region: + experts

Large Liquid Argon TPC for the NuMI Off-axis Beam

Overall efficiencies, rejection factors, and dependencies

Event type	N	pass	eff.	rej.
NC	290	4	-	72.5
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	
Beam $\bar{\nu}_e$: CC	13	10	0.77	-
NC	19	0		

Signal ν_e



Efficiency is substantial even for high multiplicity (DIS) events

Efficiency is ~100% for y<0.5, and ~50% above this

$y=E_{had}/E_\nu$

Overall efficiency 81% +/- 7%
Rejection of NC is 73 (+60,-30)

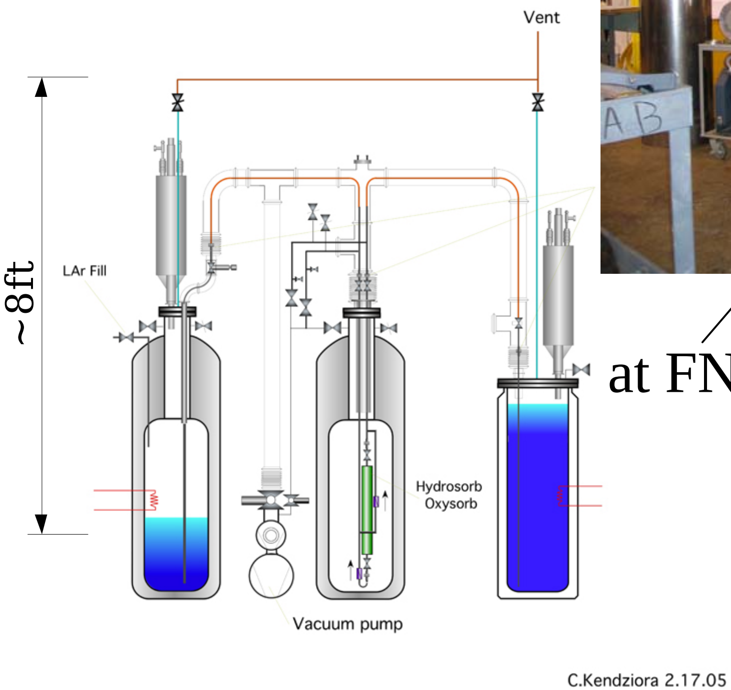
Sensitivity =
detector mass x
detector efficiency x
protons on target/yr x
# of years

Initial costing exercise, in Million $,
not fully loaded, site preparation not included;
costs are estimates from engineers involved.

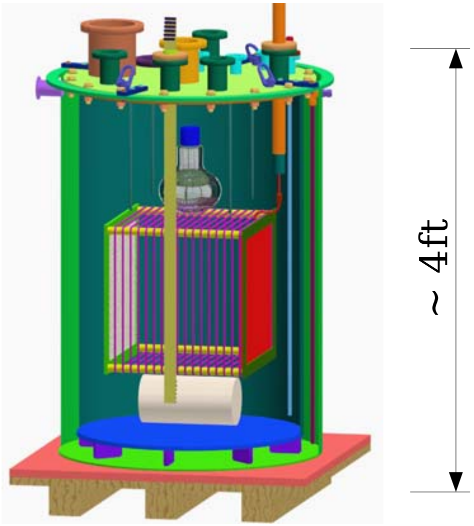
50kton 30m H x 40 m D	(M$)	15kton 20m H x 26 m D	(M$)
Argon cost	37		13
Cryogenic/ Purification plant	6.5		5.0
HV planes	5.7		4.0
Wire Chambers	5.0	→	4.0
Electronics	5.0		2.5
Data acquisition	5.0		5.0
Tank related costs	32.1		20.4
Total	96.3		53.9

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

R&D efforts underway

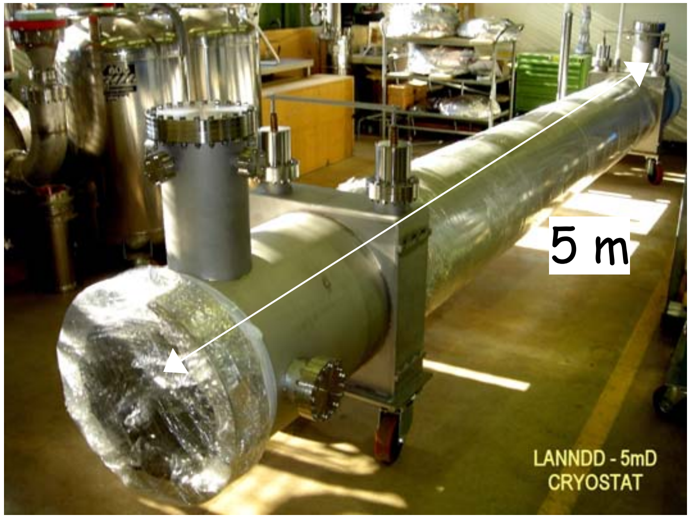


at FNAL



at Yale

UCLA/
INFN
at CERN



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

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

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

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

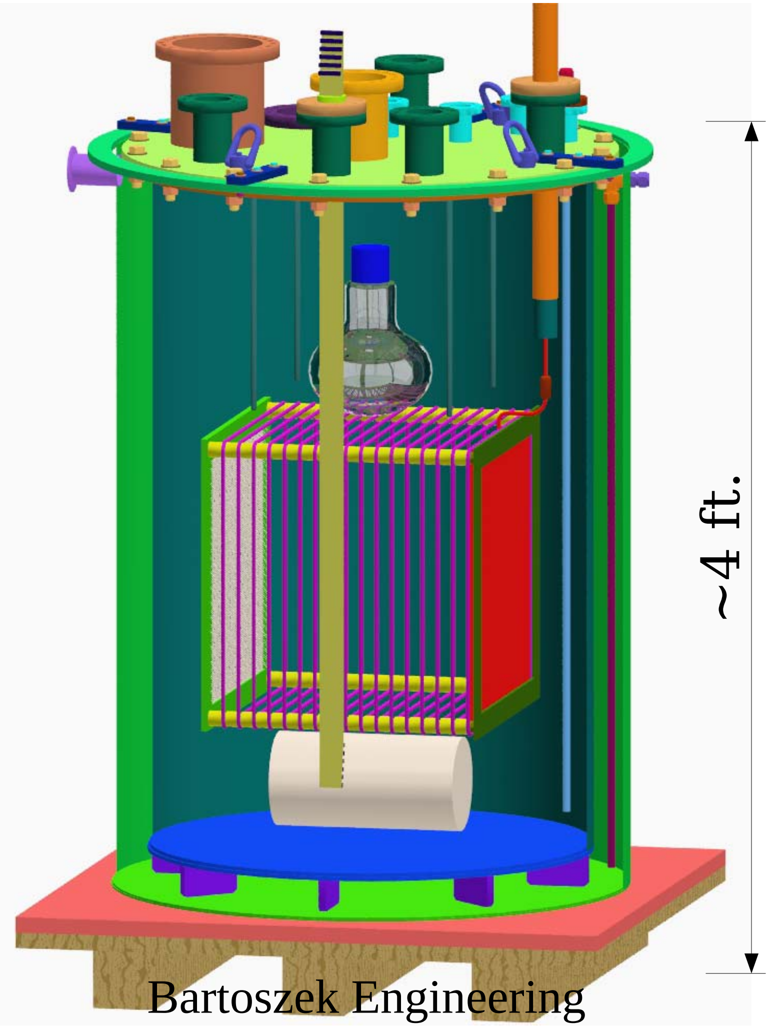
LArTPC work underway at Yale

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

↓

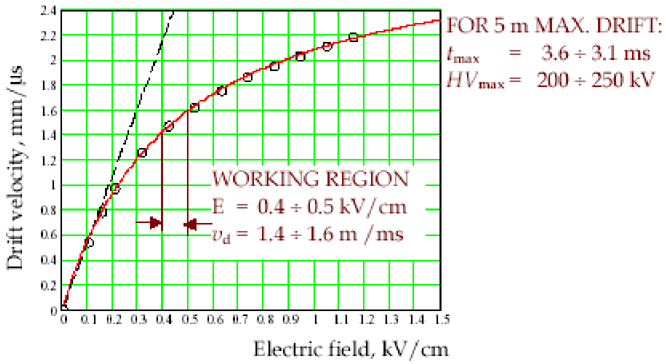
- understand the technology
- purity studies
- understand detector response at very low energies
- study combination of charge and light production for particle ID

Constructing small prototype vessel this summer

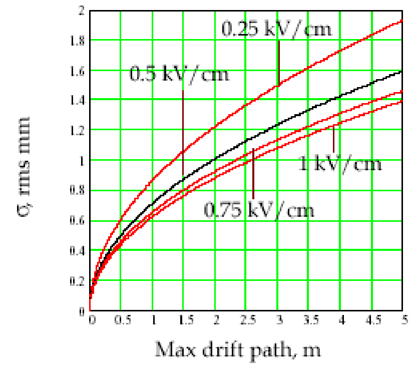


Work funded by DOE Advanced Detector Research Grant

everything about drifting in one fine slide



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

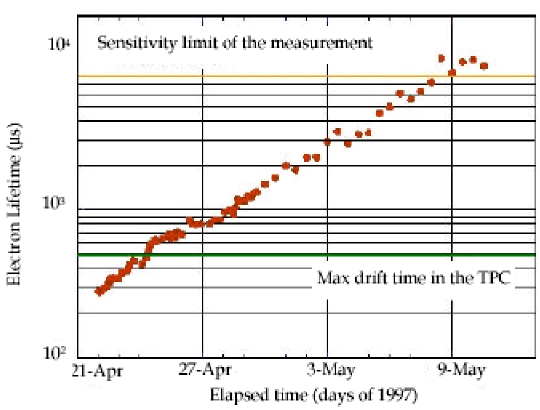
$D = 4.06\ cm^2/s$

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

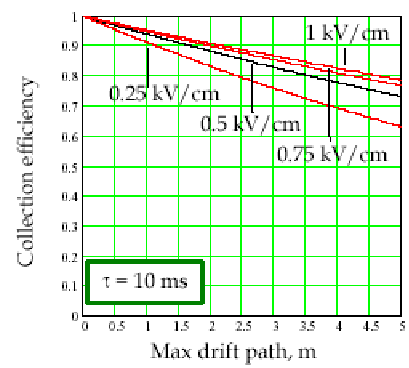
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $<\sigma_D>$ = 1.1 mm

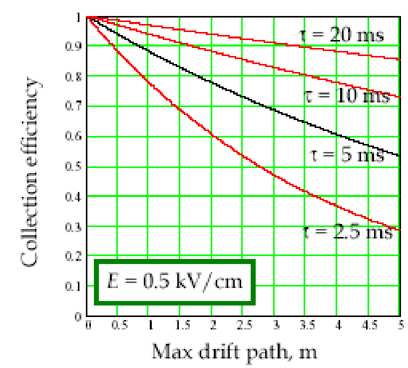
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

NuFact'01 – March 24-30, 2001   F. Sergiampietri   LANNDD 22

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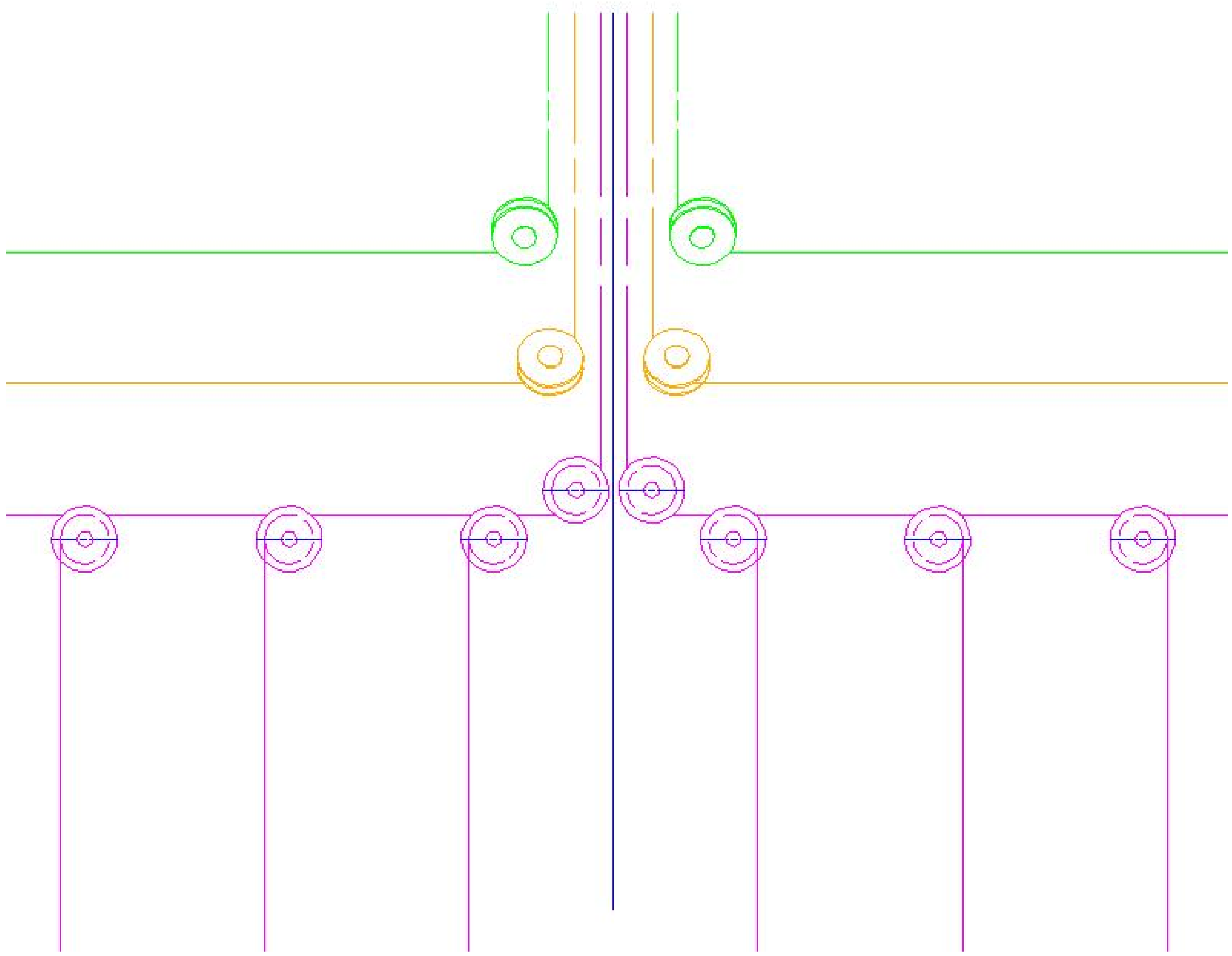
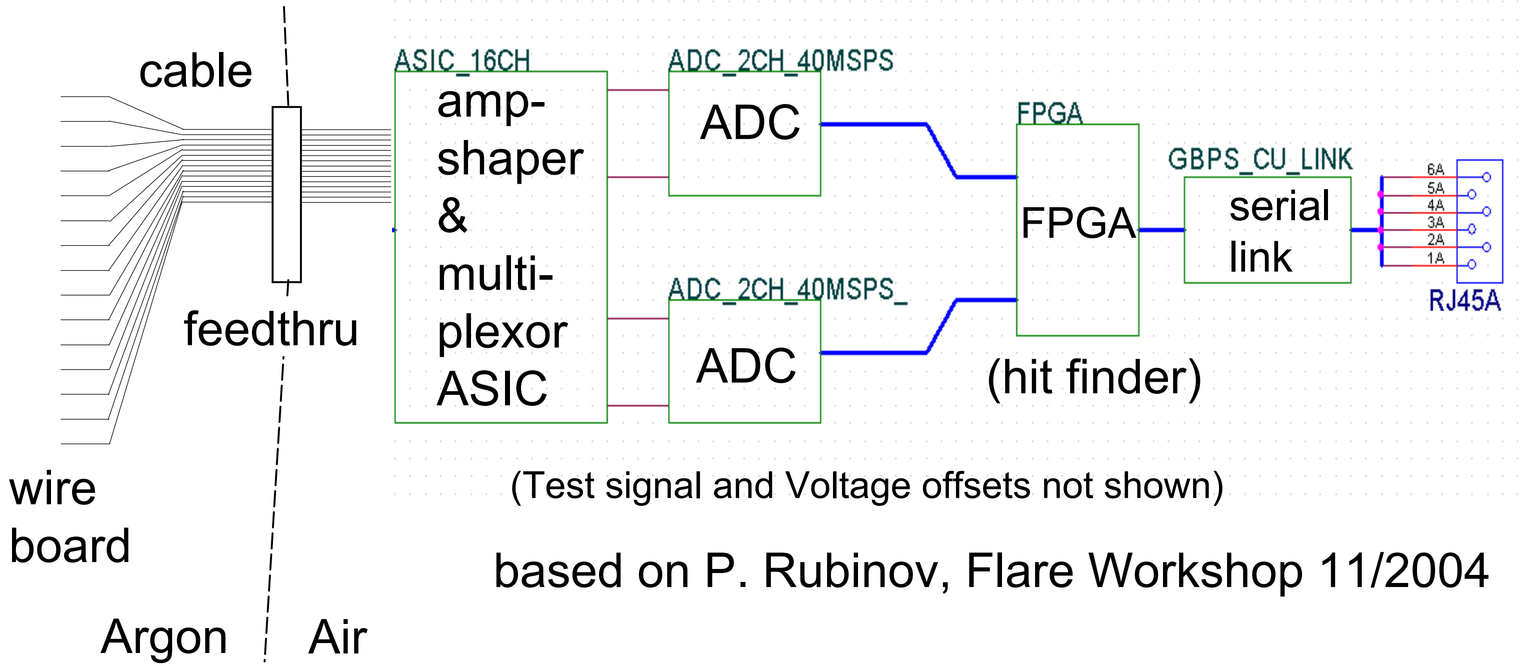
setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly in PAB at FNAL.

Large Liquid Argon TPC for the NuMI Off-axis Beam

Expanded view of wire arrangement at base of tank



general electronics schematic

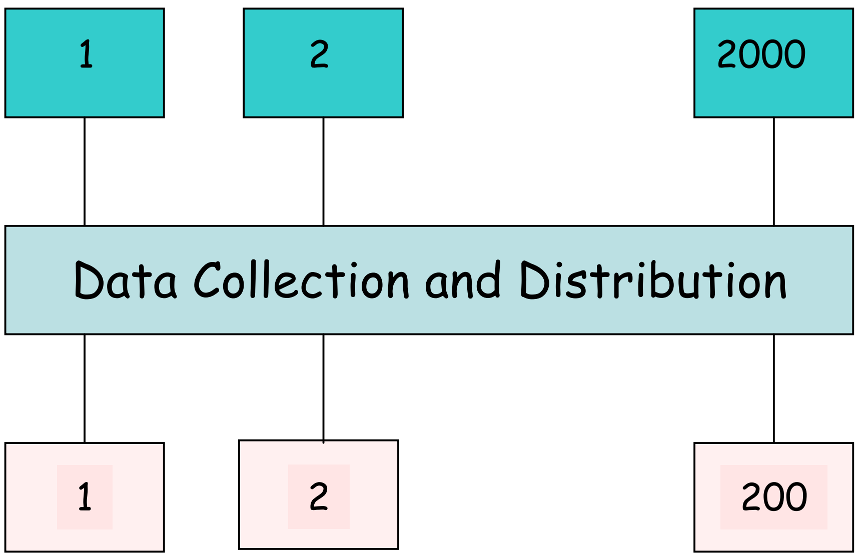


based on P. Rubinov, Flare Workshop 11/2004

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

Data Acquisition schematic

General Scheme using commercial links and switches



Front-end Boards (1000 - 2000)

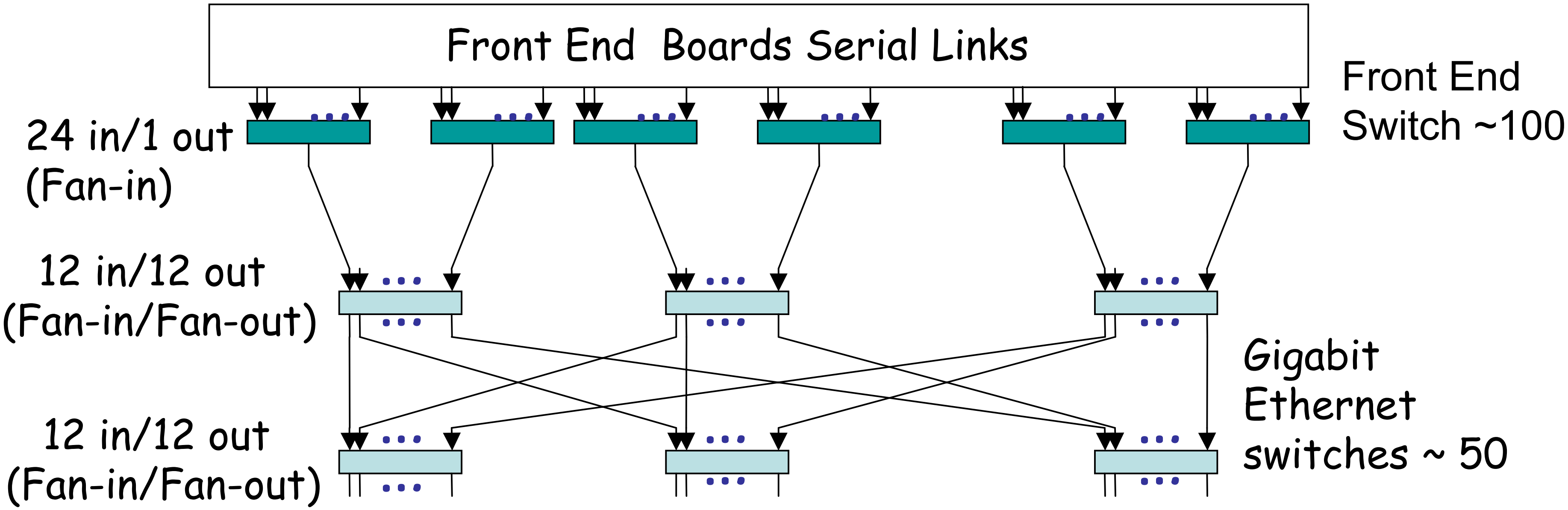
Ethernet Network

Processors (for online reconstruction)

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

Data Acquisition Schematic

commercial switches well matched to required data rates.

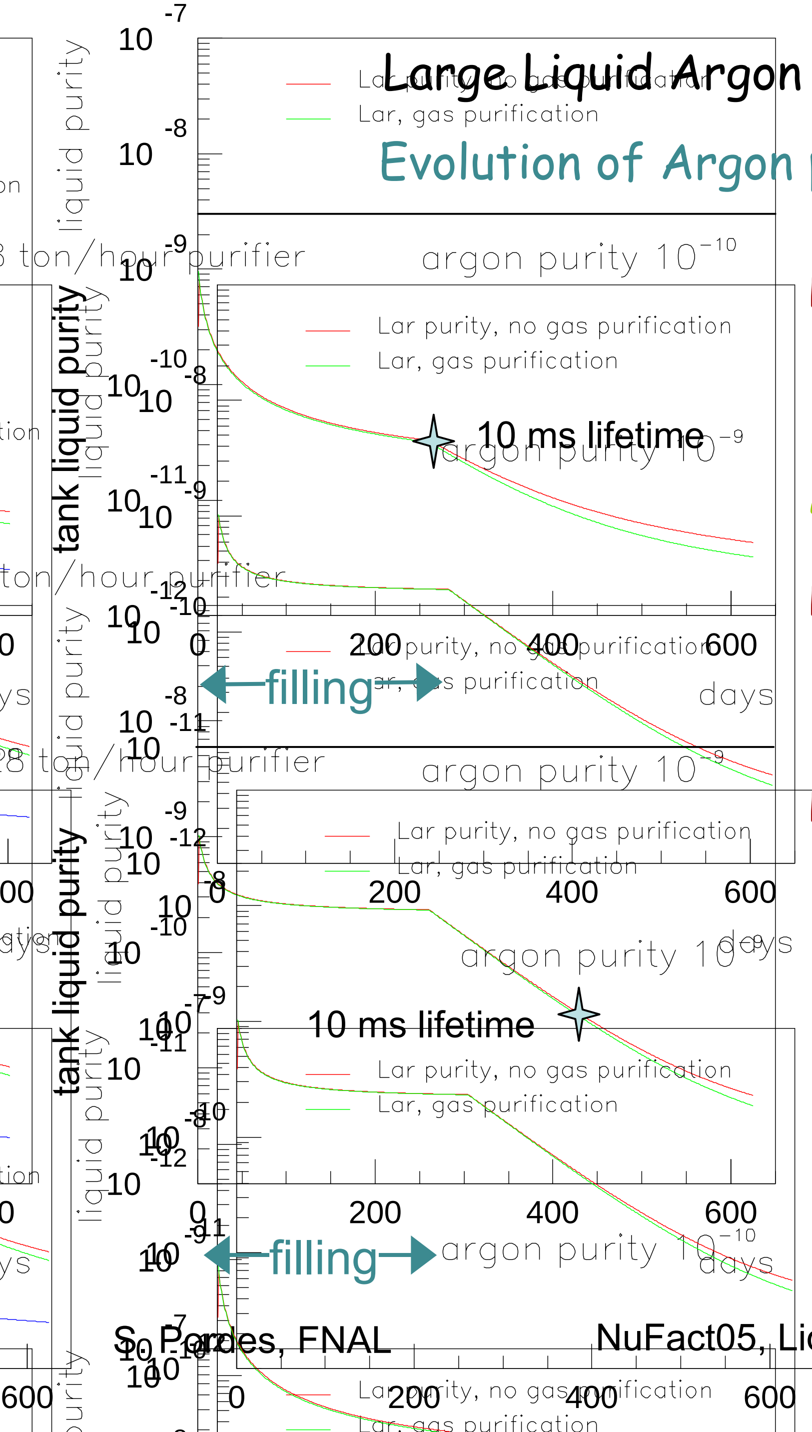


allows for 5 GByte/sec rate into ~ 200 Processors

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

Large Liquid Argon TPC for the NuMI Off-axis Beam

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

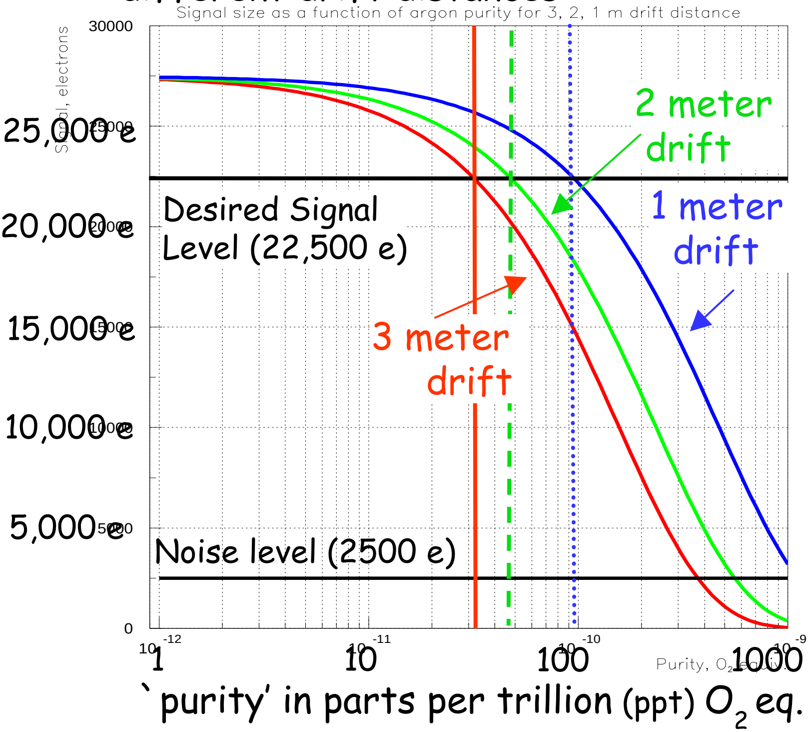
Phase III: operation

- Low rate of volume exchange (74 days)
- Removal (mainly) of the impurities introduced with new argon
- Balance between purification and out-gassing
- In this phase out-gassing of tank walls, cables and other materials becomes a visible factor.

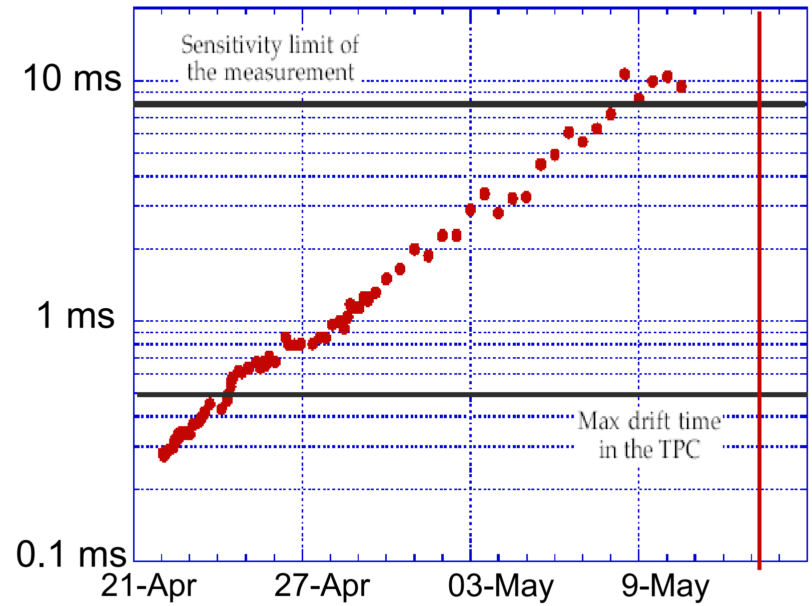
Large Liquid Argon TPC for the NuMI Off-axis Beam

Liquid Argon `purity' requirements

Signal size vs `purity' for different drift distances



data from ICARUS 1997



`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