The Neutrino Detector of the Future: A Massive Liquid Argon TPC

J. Strait
Fermilab
October 21, 2005

Neutrino Masses and Mixing

Understanding neutrino masses and mixing may give clues to

- physics at the GUT scale => "see-saw" mechanism
- origin of matter excess over anti-matter => leptonic CP violation

ν mixing is large:

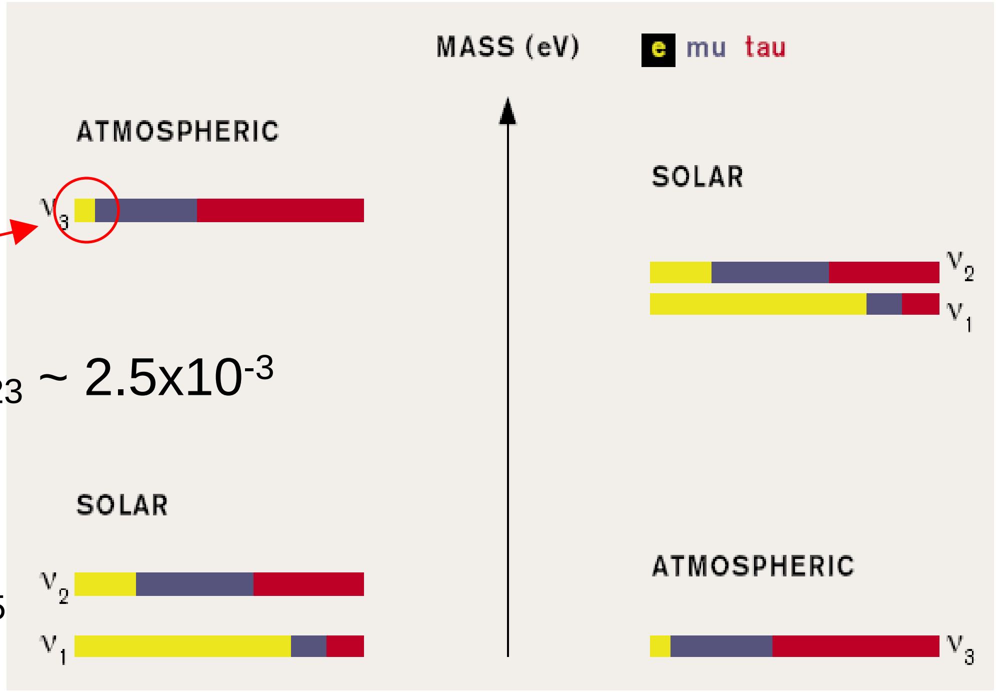
$\sin^2 2\theta_{23} > 0.92$

$\sin^2 2\theta_{12} = 0.82 \pm 0.07$

$\sin^2 2\theta_{13} < 0.14$

$\Delta m^2_{23} \sim 2.5\text{x}10^{-3}$

$\Delta m^2_{12} \sim 8\text{x}10^{-5}$



"Normal" "Inverted"

$\nu_\mu \to \nu_e$ is the next step

CP violating phase δ appears with θ_{13} in the MNS matrix:

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

where $c_{ik} \equiv \cos\theta_{ik}$ and $s_{ik} \equiv \sin\theta_{ik}$.

And θ_{13} is measured by ν_e appearance in a ν_μ beam:

$$P_{vac}(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2 1.27\left(\frac{\Delta m_{32}^2 L}{E}\right)$$

ν_e Appearance Measurement

For ν_e appearance measurement, we need:

- Long baseline
  => 1^{st} oscillation max is at ~800 km for E_ν ~1.5 GeV
  => matter effect to determine sign(Δm^2_{23})

- High sensitivity to ν_e charged current events

- Good background rejection against π^0's in ν_μ neutral current events.

BNL Proposal 704

ν_e appearance experiment proposal, 1977.

A STUDY OF THE TIME EVOLUTION OF A LONG-LIVED ν_μ BEAM

E. Egelman, B. Gordon, W. Kozanecki, W. Loomis, J. LoSecco, C. Rubbia, A. Sessoms, D. Shambroom, J. Strait, L. Sulak, C. Tao, R. Wilson and M. Yudis

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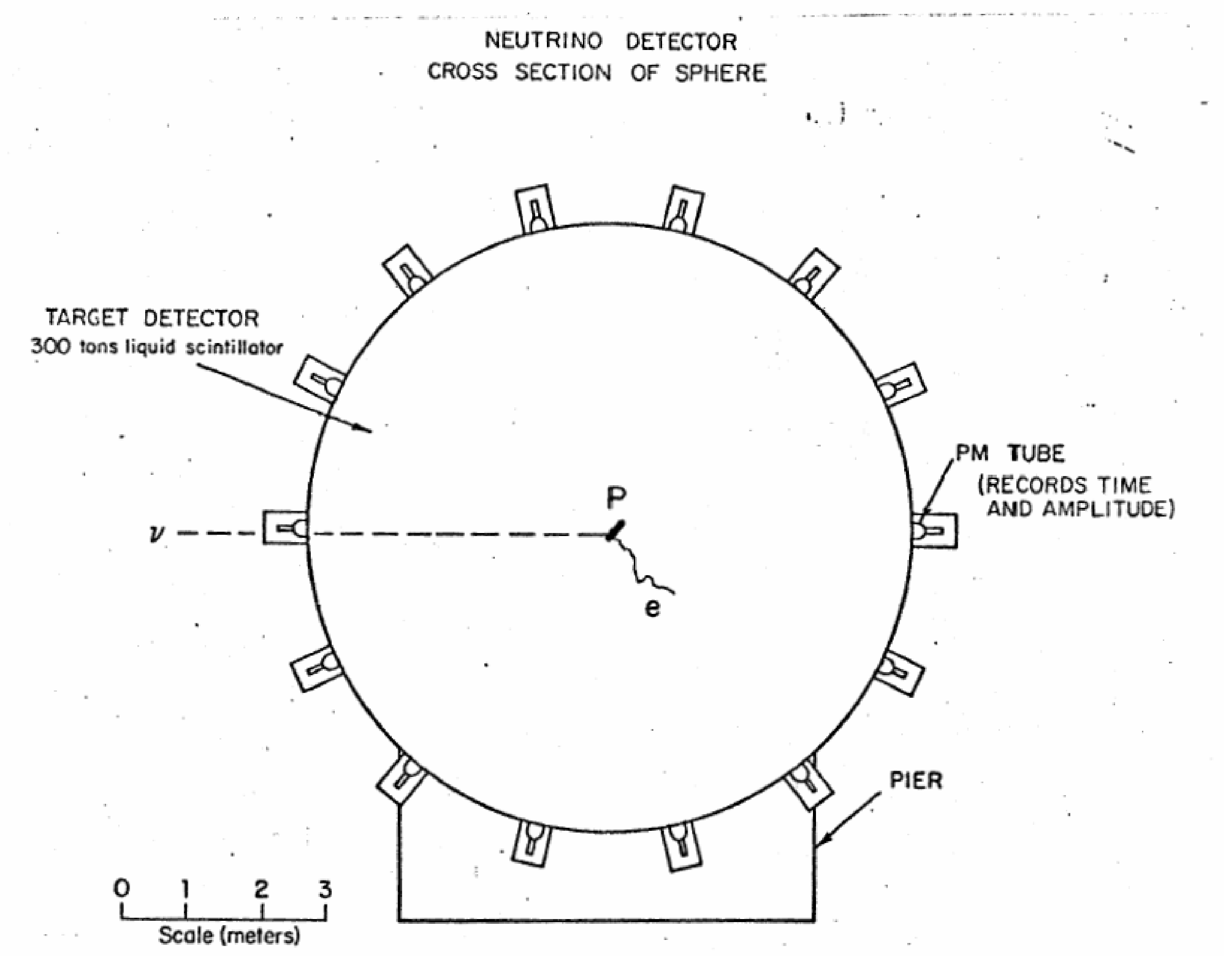
Abstract

We propose to study the time evolution of a long-lived ν_μ beam at Brookhaven National Laboratory. Sensitivity at large proper times $\tau = \ell/p$ (where ℓ is the flight length and p is the momentum of the neutrino) is achieved by going to low neutrino momentum. The AGS proton momentum is chosen to concentrate the ν_μ flux at very low energy where all background reactions are kinematically suppressed. In particular $\nu_\mu \to \nu_e$ transformations are sensed via $\nu_e n \to e^- p$ or by the classic reaction $\nu_e + C_{12} \to N_{12} + e^-$ followed by a delayed $N_{12} \to C_{12}\, e^+ \nu_e$ signal. We propose (1) a 300 T detector for the definitive experiment and (2) an early exploratory test with the existing Brookhaven neutrino detector.

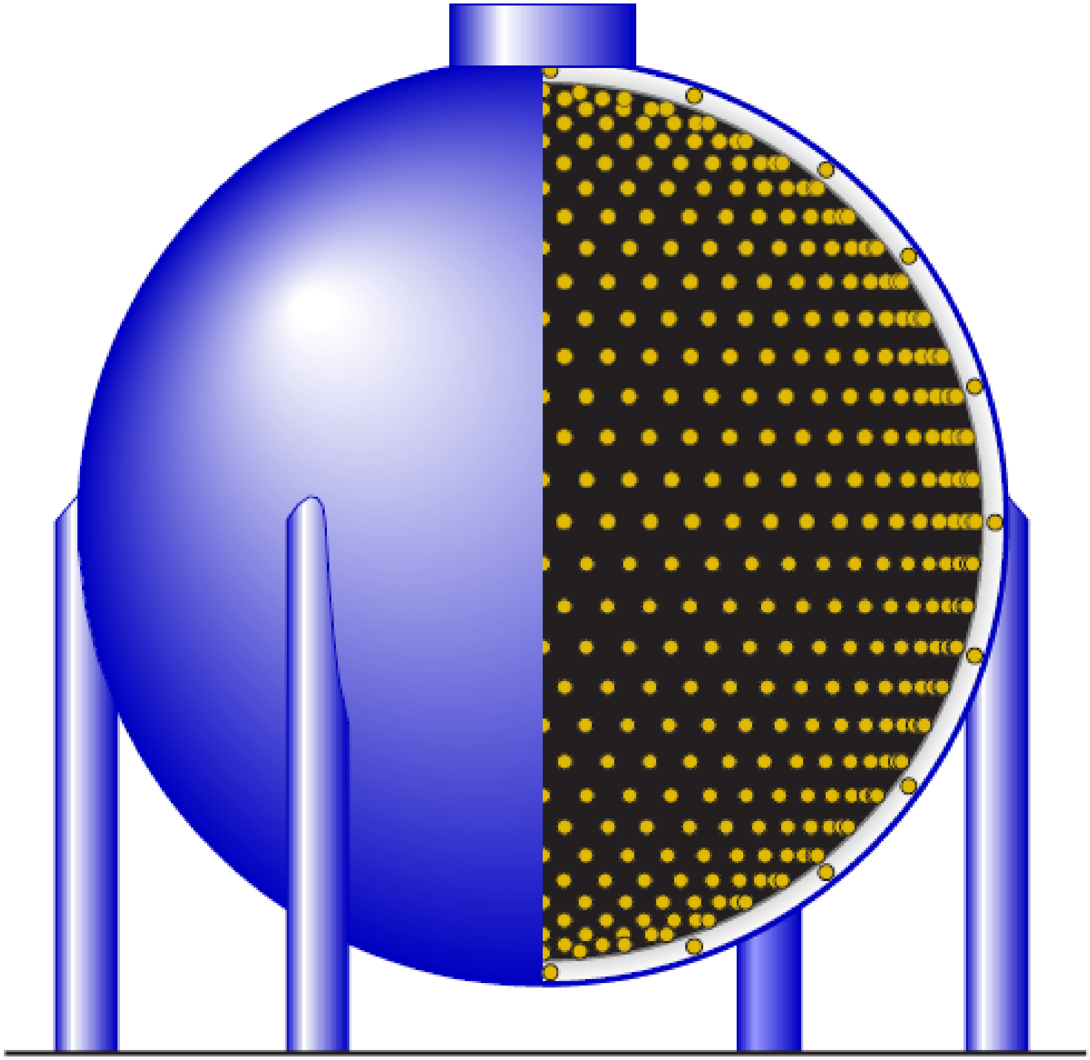
17 January 1977

Submitted to Brookhaven National Laboratory

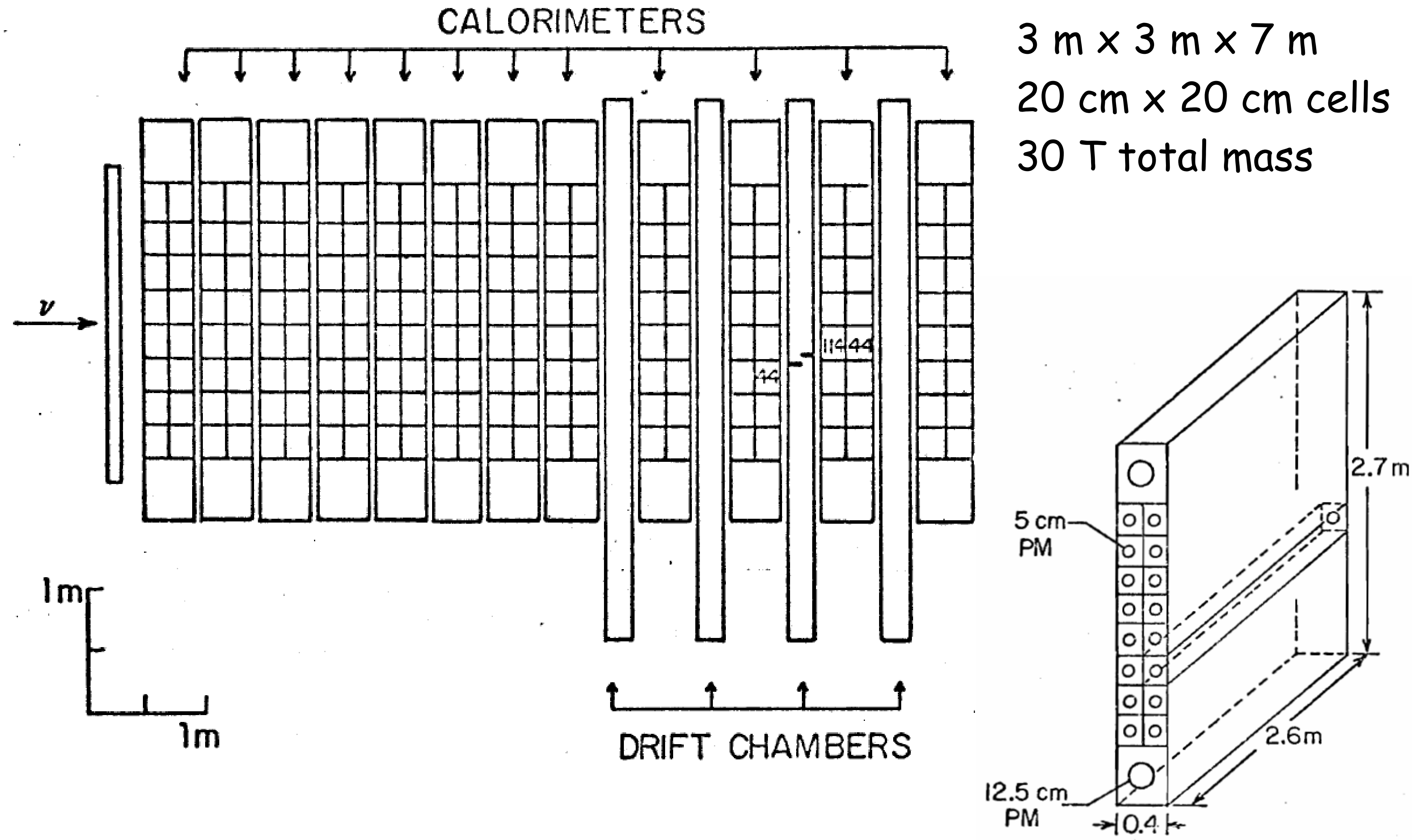
Proposed detector for short baseline, low-E $\nu_\mu \to \nu_e$, 1977



Actual detector for short baseline, low-E $\nu_\mu \to \nu_e$, Today



Fine-grained, totally active ν Detector, ca. 1975
BNL E613

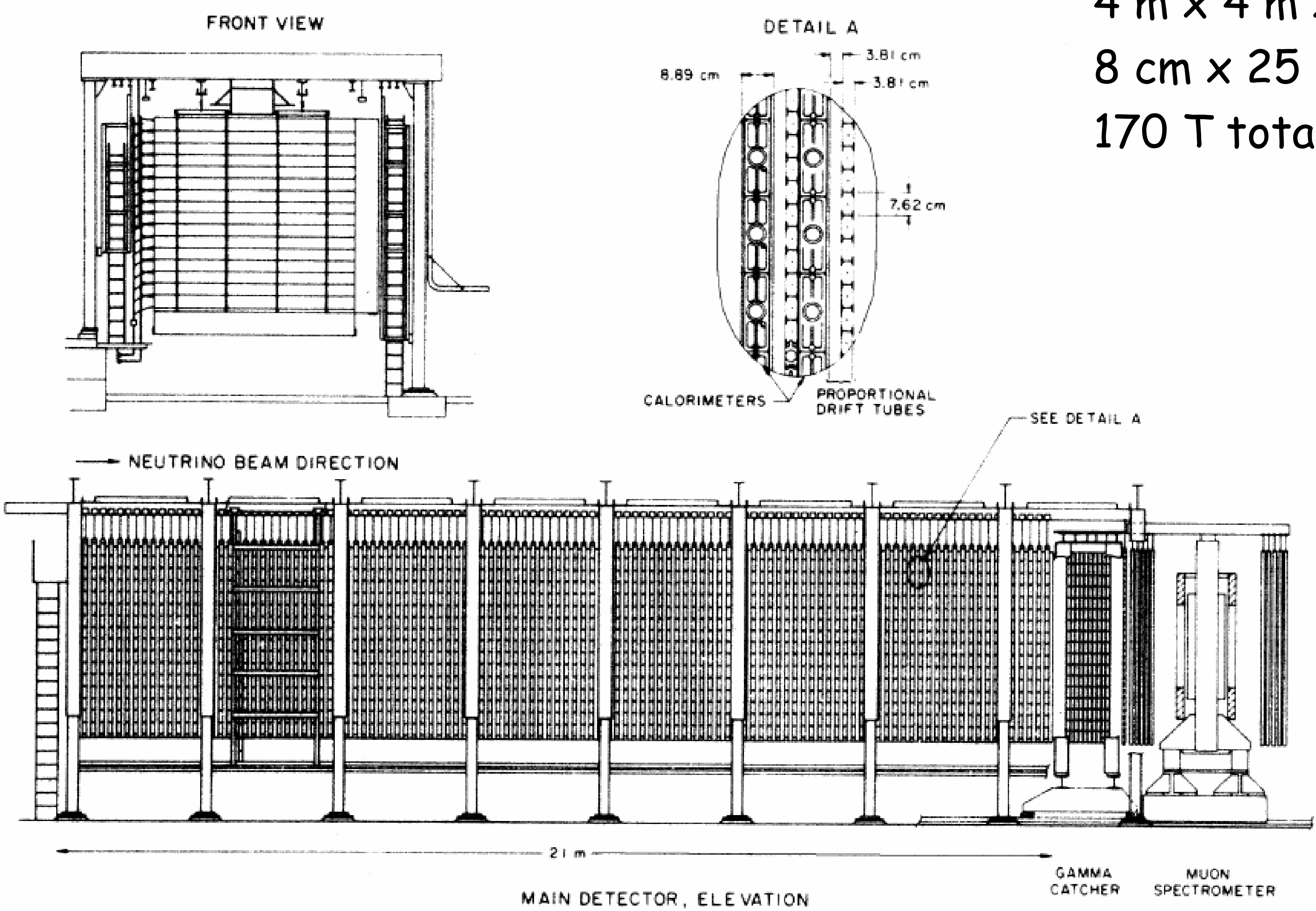


3 m x 3 m x 7 m

20 cm x 20 cm cells

30 T total mass

Fine-grained, totally active ν Detector, ca. 1985
BNL E734

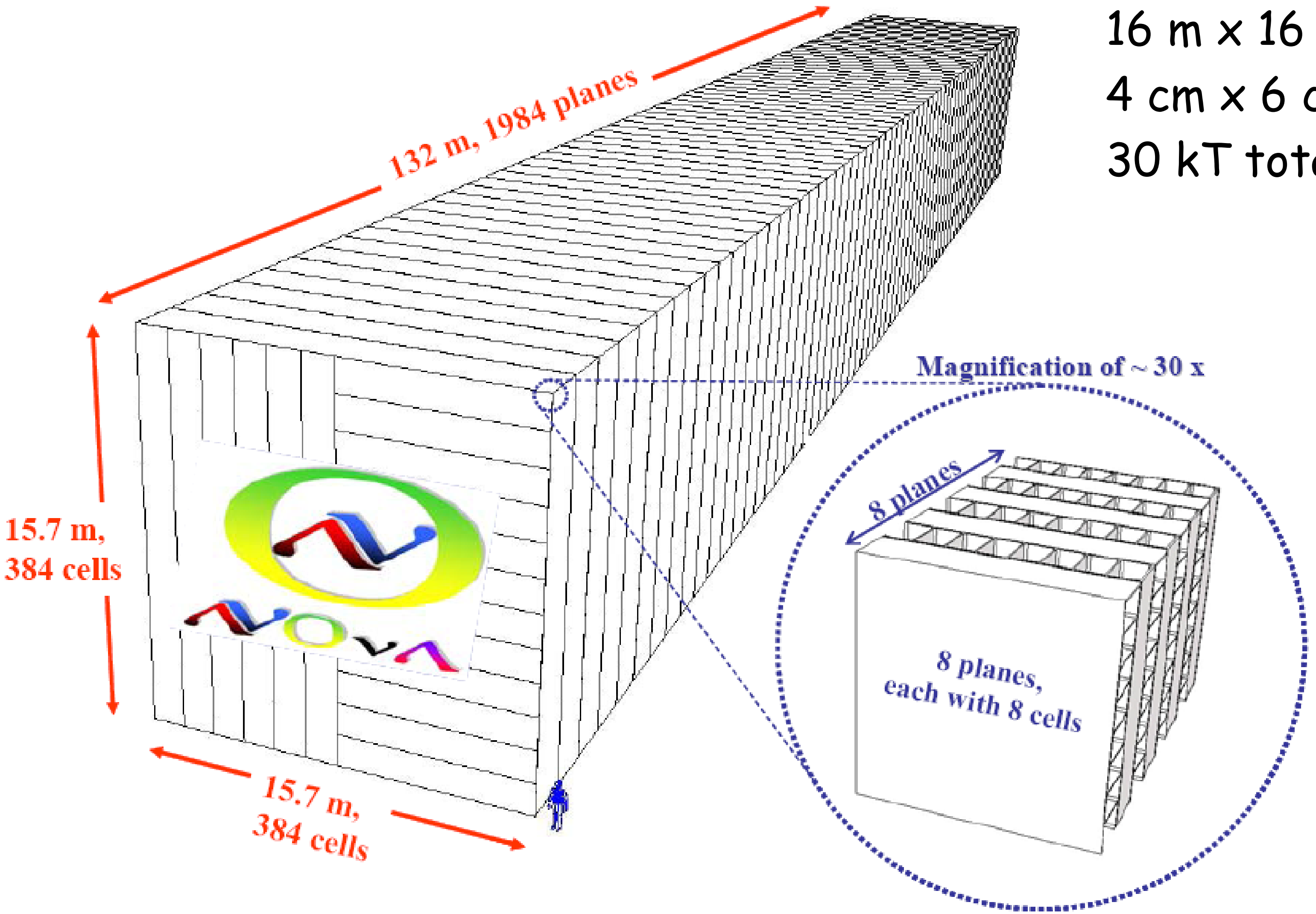


4 m x 4 m x 21 m

8 cm x 25 cm cells

170 T total mass

Fine-grained, totally active ν Detector, ca. 2010
NOνA in Fermilab NuMI beam

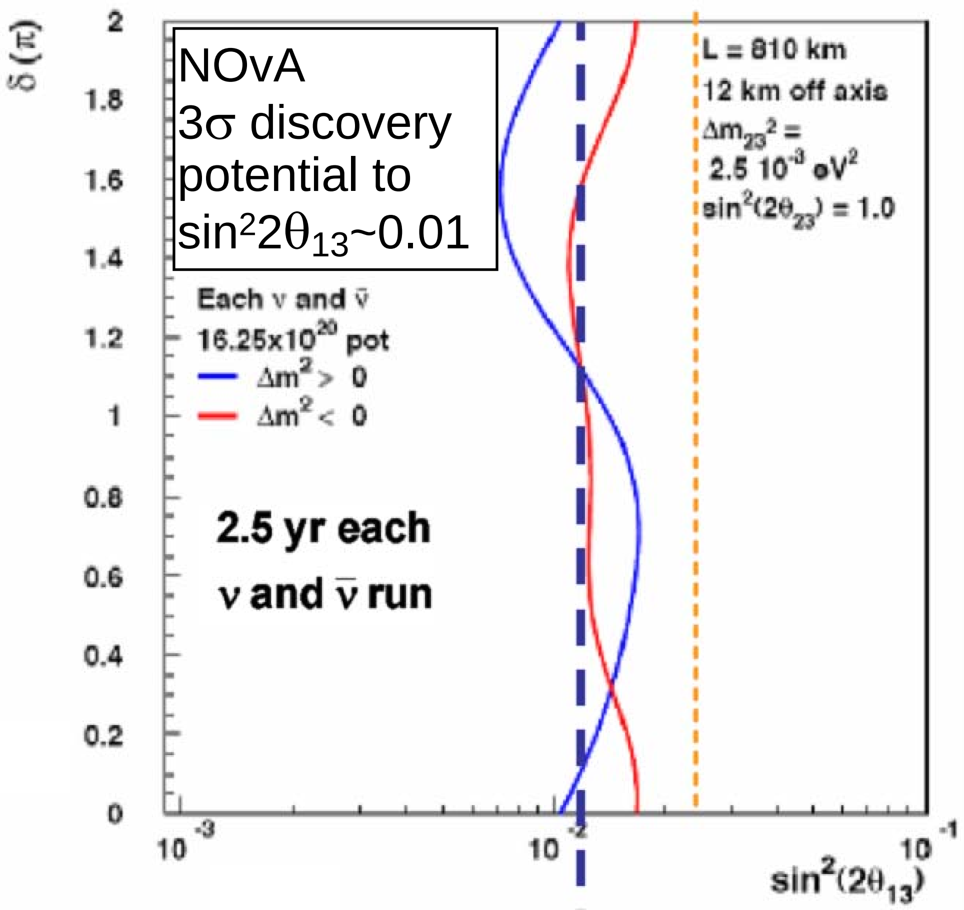


16 m x 16 m x 132 m

4 cm x 6 cm cells

30 kT total mass

NOvA Discover Reach



Discovery reach (3σ)

- $\sin^2 2\theta_{13}$ to 0.007~0.02, depending on the unknown sign of Δm^2 and value of δ (T2K is comparable)
- mass ordering for $\sin^2 2\theta_{13} > 0.04$, depending on the unknown value of δ (nothing useful from T2K alone)
- Non-zero chance to see CP violation for $\sin^2 2\theta_{13} > 0.02$ (T2K is comparable)

=> *We will need more sensitive experiments beyond the current round.*

Extending ν Oscillation Sensitivity

Sensitivity of a neutrino experiment is proportional to the product

beam flux × detector mass × detection efficiency.

NuMI Beam flux ~ average proton beam power on target

- 0.25 MW now (currently the world's most powerful ν beam)
- 0.4 MW by 2008 with planned upgrades
- 0.6 MW in 2010 when the Tevatron is turned off (comparable to JPARC in 2011)

Further improvements: aimed at 2 MW proton beam power

- Proton Driver (8 GeV SC linac)

  Provides 2 MW at any energy 8 -> 120 GeV.
- Also develop alternatives:

  We have VERY EARLY ideas on how to deliver 1+ MW at 120 GeV using pbar source rings when Tevatron is shut down.

Liquid Argon TPC:
An affordable (?) way to high mass x efficiency

Massive LAr TPC provide a potential means to extend our reach in neutrino physics.

- Charge can be drifted long distance in (very pure) LAr with little diffusion.
- Fine-grained (~1 mm) tracking, total absorption calorimeter with improved electron efficiency and background rejection.
- ICARUS has demonstrated the technical feasibility of this technique in a "small" 600 T detector.
- Sketches and some preliminary engineering has been done that indicate a path for realizing larger detectors in the 10-50 kT range.

Much R&D must be done to demonstrate that this technology can be scaled to the masses of interest for long-baseline neutrino physics.

An LAr TPC could also be important for other physics, most notably proton decay.

A Little History

The idea of a Liquid Argon TPC for neutrino physics is not new.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

G E N E V A

1977

1st measure-ments of macroscopic (7 cm) electron drift in LAr . . . λ_d > 50 cm.

IEEE Transactions on Nuclear Science, Vol.NS-25, No.1, February 1978

FURTHER OBSERVATION OF IONIZATION ELECTRONS DRIFTING IN LIQUID ARGON

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Measurements using a ^{137}Cs internal conversion source demonstrate that ionization electrons will drift at least 35 cm in liquid argon in electric fields of a few kV-cm^{-1}.

I. Introduction

Liquid argon ionization detector technology is advancing at a rapid pace following the recent efforts of Willis[1] and others.[2,3] The initial design of such detectors made use of inert inserts within the liquid argon, both as electrodes and as converters for electromagnetic and/or hadronic cascades. It was recognized early that these inserts degrade the energy resolution of such calorimeters. The first liquid argon shower counters were made with many thin converter sheets in order to minimize this effect. Eventually, the suggestion was made that inert converters should not be used at low energies to achieve optimal energy resolution, and wire planes were introduced as electrodes.[4] Such detectors have totally sensitive volumes and, if sufficient spacial resolution could be achieved, these detectors would have unique capabilities and could be favorably compared with bubble chambers.

This was recognized, and such a detector was proposed to Fermilab for a four Fermion leptonic scattering experiment.[5] However, it was clear that spacial resolution of a few millimeters with closely spaced wire planes led to technical as well as financial difficulties. Thus, the idea of drifting ionization electrons over large distances in liquid argon and collecting the induced charge as a function of time[6] was introduced and actively discussed.

The capability to drift electrons over large distances in liquid argon is basic to the feasibility of this idea. Information from detectors which collected ionization electrons over distances of a few millimeters, was encouraging.[7] It is well known that electronegative impurities, especially oxygen, must be at very low levels. Typically, oxygen levels of a few parts per million in argon[8] can be tolerated.

before. Argon gas purification/handling and cryogenic systems are shown in Fig. 2. Argon gas is purified by the sequence: (a) Hydrox purifier;[10] (b) molecular sieve, 13X,[11] at 293° K; (c) molecular sieve, 4A,[11] at 196° K. Oxygen impurity is measured with a trace oxygen analyzer[12] which has a rated sensitivity to O_2 concentration at the level of 0.1 ppm. The liquid argon detector is kept cold by immersing it in a bath of liquid nitrogen. The nitrogen is pressurized to 30-40 psig in order not to freeze argon.

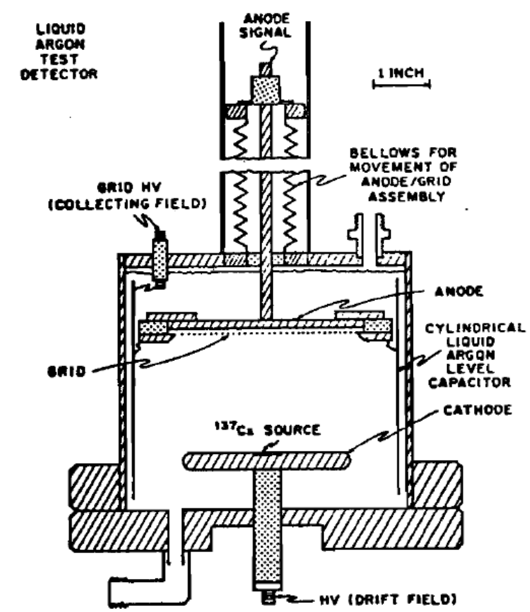
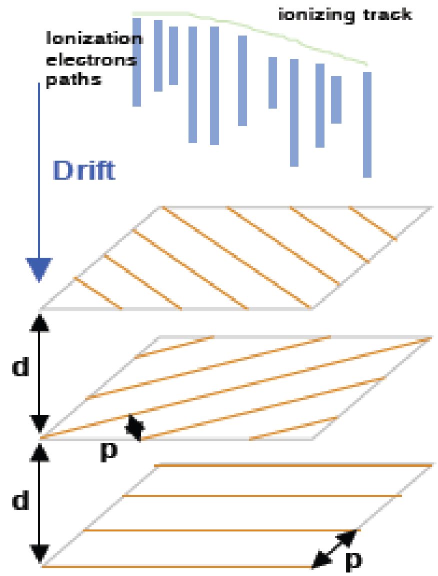
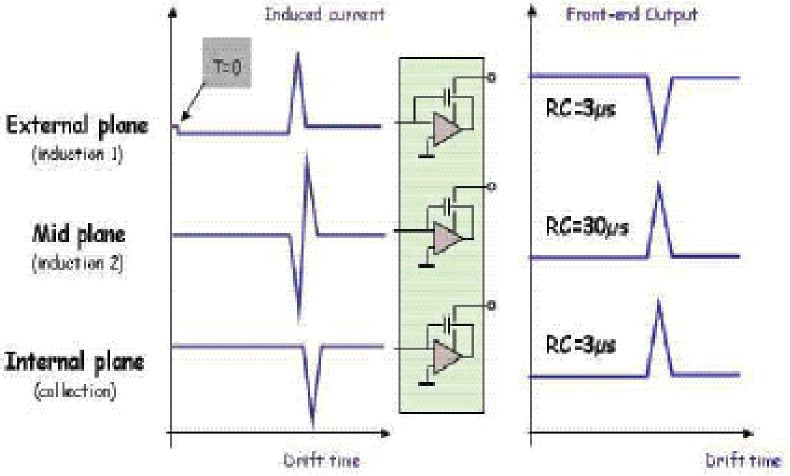


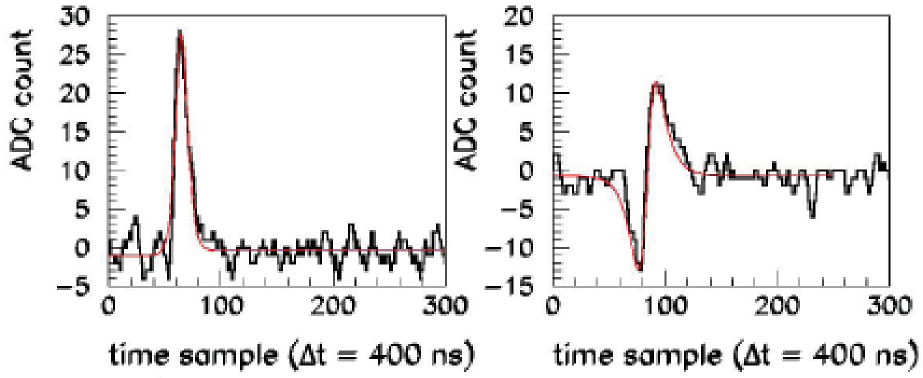
Figure 1. Schematic of detector for measuring ionization electron drift distance in liquid argon.

Signals on wire chamber planes



Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge

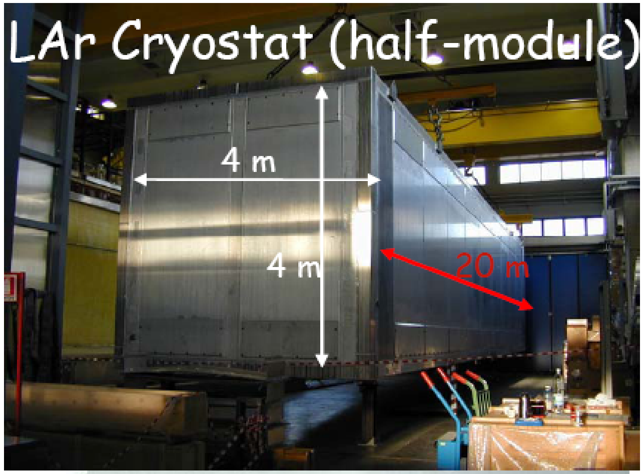


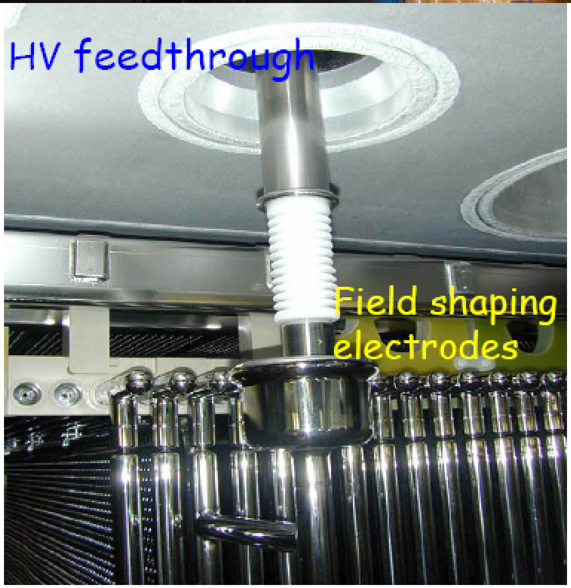


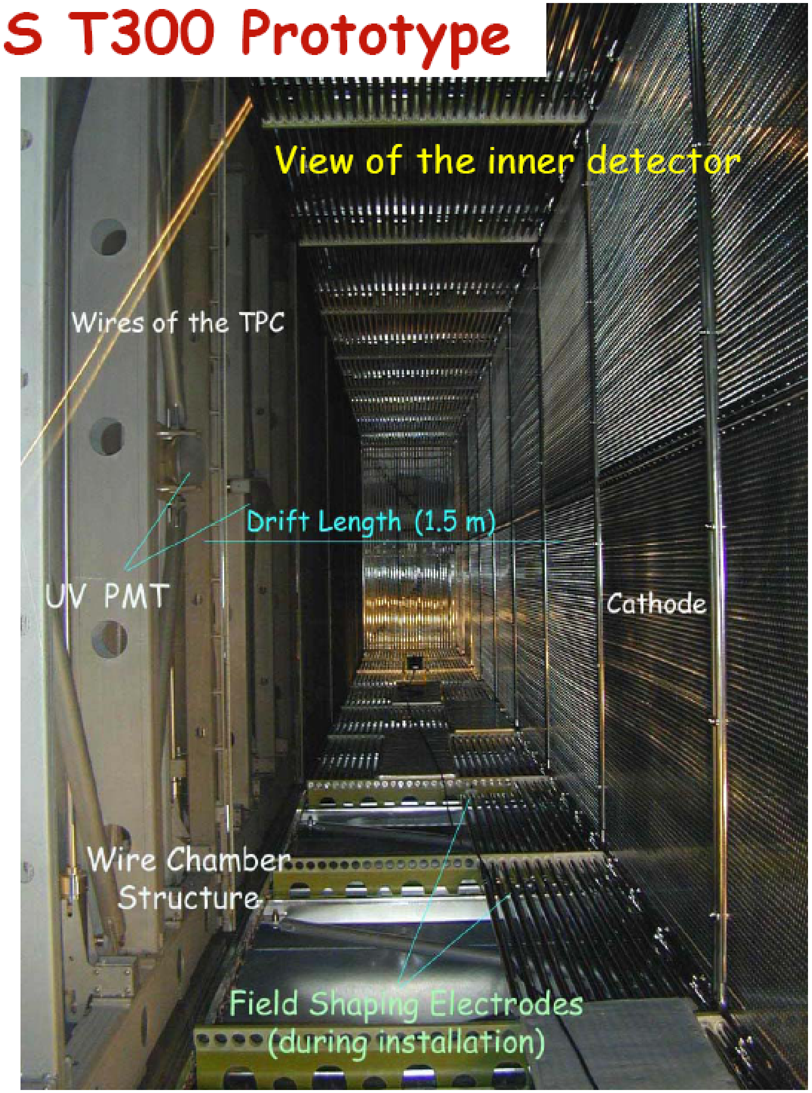
ICARUS TM/2001-09

ICARUS is "proof of principle"

ICARUS T300 Prototype

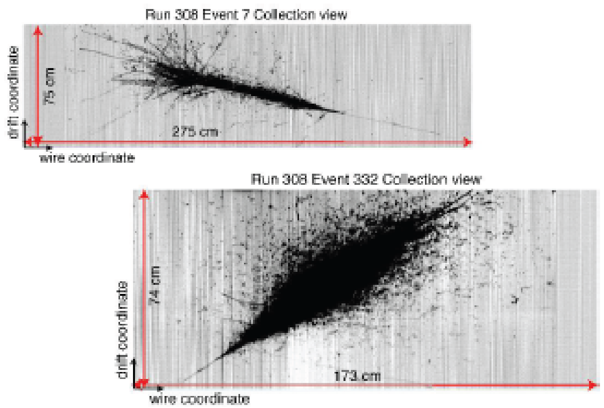


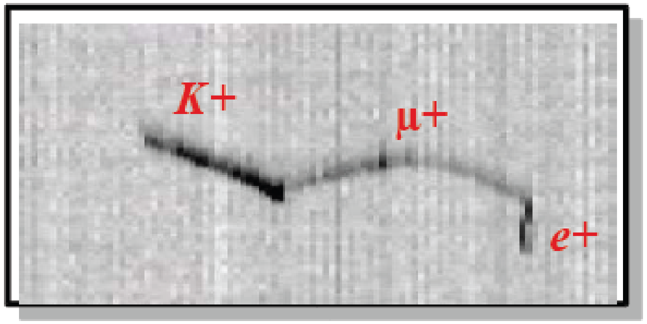




Two 300T modules (one shown here) with 1.5 m drift length.

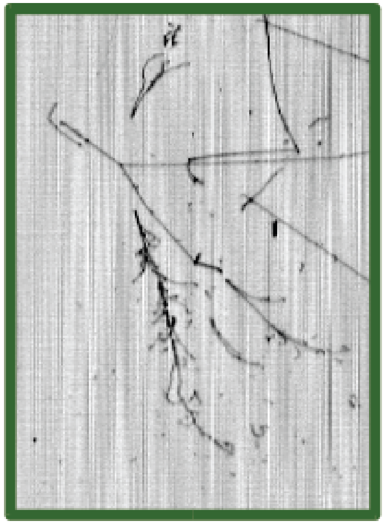
Sample ICARUS Events

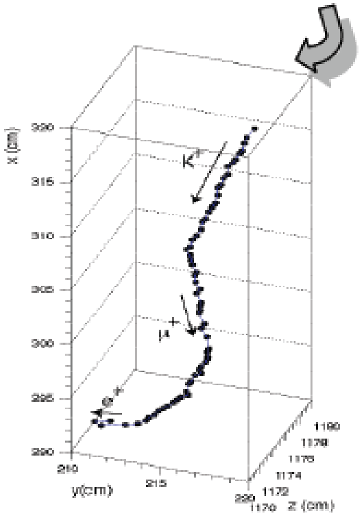




data

data





ICARUS images

Simulated Neutral Current Event with 1 GeV π^0

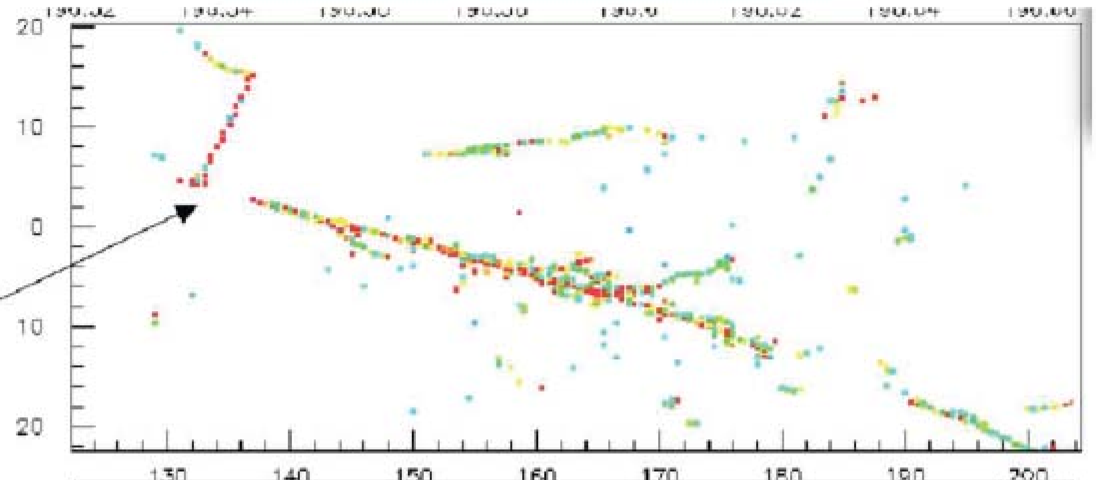
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

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

3.5% X_0 samples

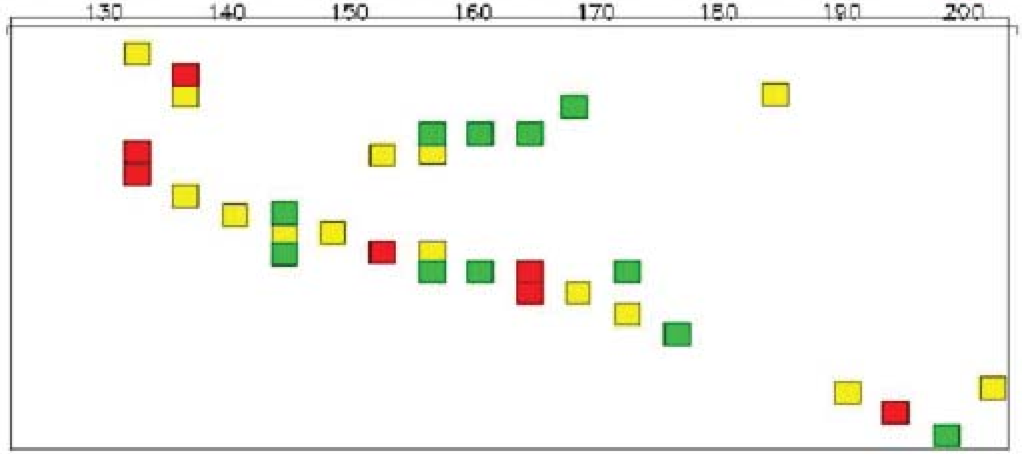
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



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.

- Baseline 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;

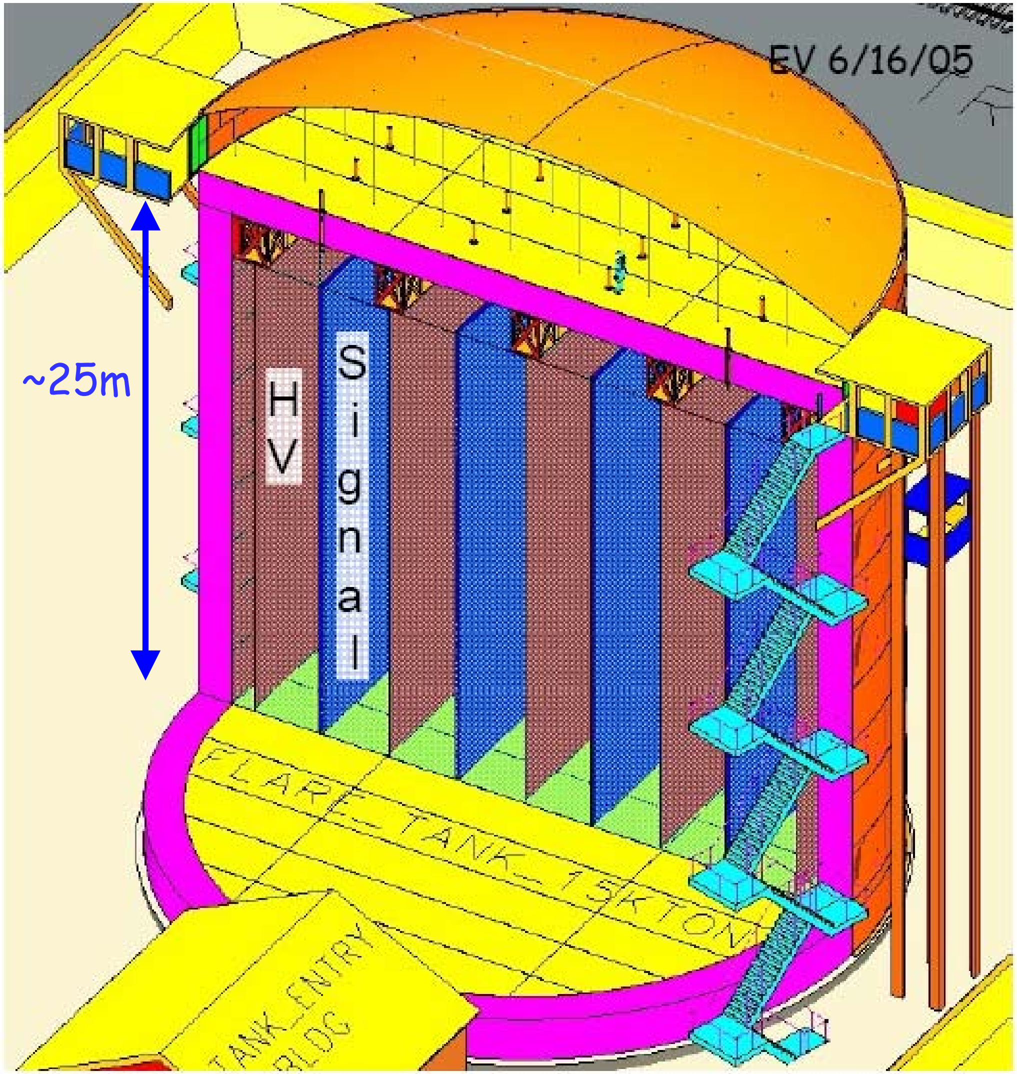
- Construction of detector tank using industrial LNG tank as basic structure
- Long(er) signal wires
- Single device (not modular)

Requires <0.03 ppb O_2 for <20% signal loss

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)

Large Liquid Argon TPC for the NuMI Off-axis Beam



3D `Model' cutaway
15 kt detector

50 kT: 40 m dia. x 30 m high

Changes from standard LNG tank:

inner tank wall thickness increased
- LAr is 2 x density of LNG;

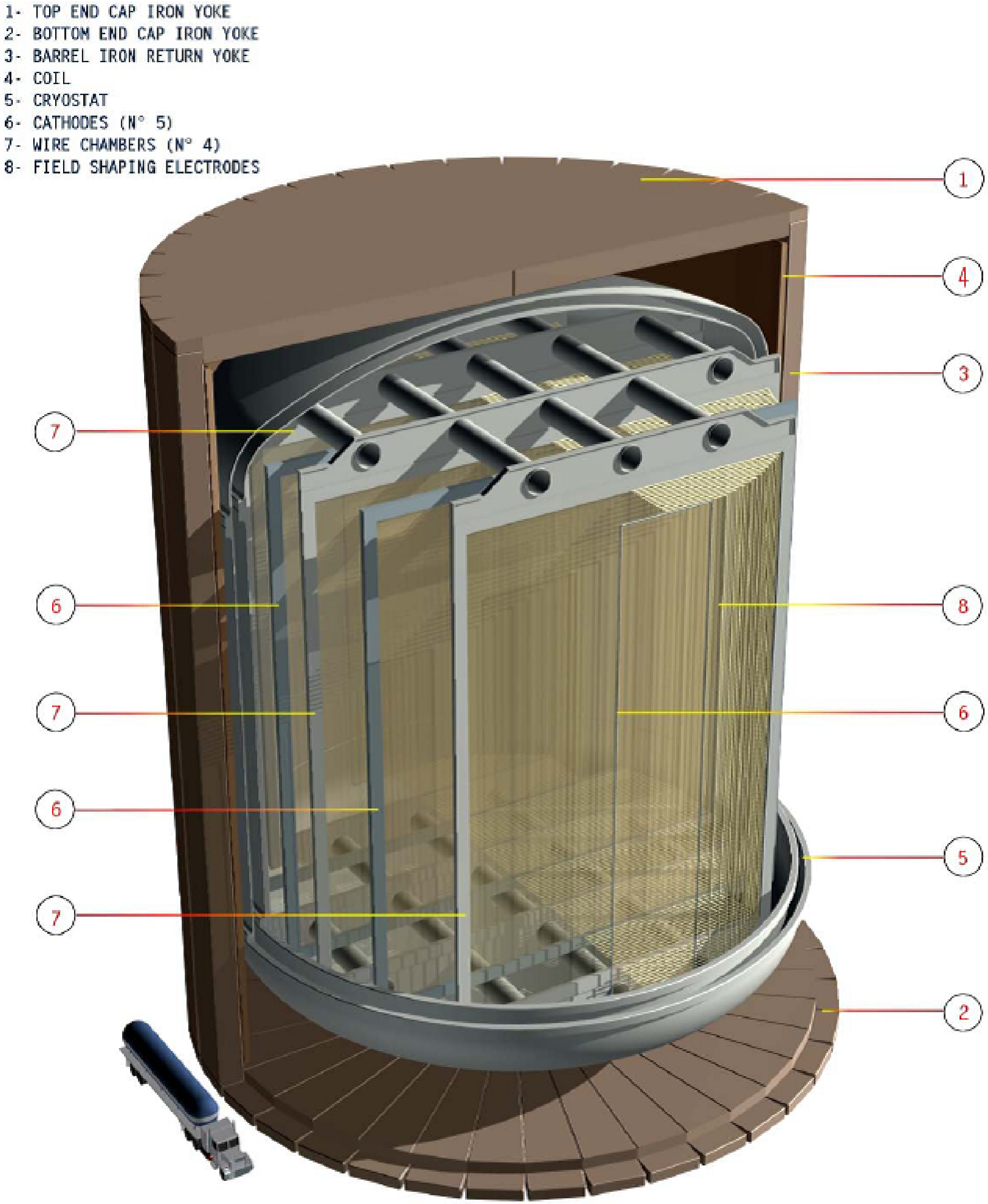
trusses in inner tank to take load of the wires:

penetrations for signals from inner tank to floor supported from roof of outer tank;

Approximately the volume of the Dzero assembly hall between the shield wall and the clean room

A 70 kT Magnitized(!) concept (LANNDD)

(D.Cline,
J.Learned,
K.McDonald,
F.Sergiampetri)



Some Specific challenges:

Argon: (long drift)

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

Thermodynamics of large volumes of LAr

Wire-planes:

long wires - mechanical robustness, tensioning, assembly, breakage/failure

Cost-effective ways of stringing 100k's of wires.

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

100k's of channels => cost/channel may be cost driver.

(and there are others for example, High Voltage)

Argon receiving, quality control, purification systems

- Critical set of issues, clearly. More work needed to have them under full control, clearly. Design and specification process has started (FLARE notes 24,26,27,29)
- Experimental effort on proving validity of the underlying assumptions (purification power of commercial filters, effect of impurities on the electron lifetime, composition of impurities, out-gassing rates, time dependence) underway (PAB setup, Lab 3)

~10 kT/mo

- 10,000 l/h (2,640 gph)
- 3 m H x 1.4 m W x 2 m D
- 2,500 Kg
- NEMA 4X cabinet
- 0°C to 40°C standard
- -20°C to 40°C option

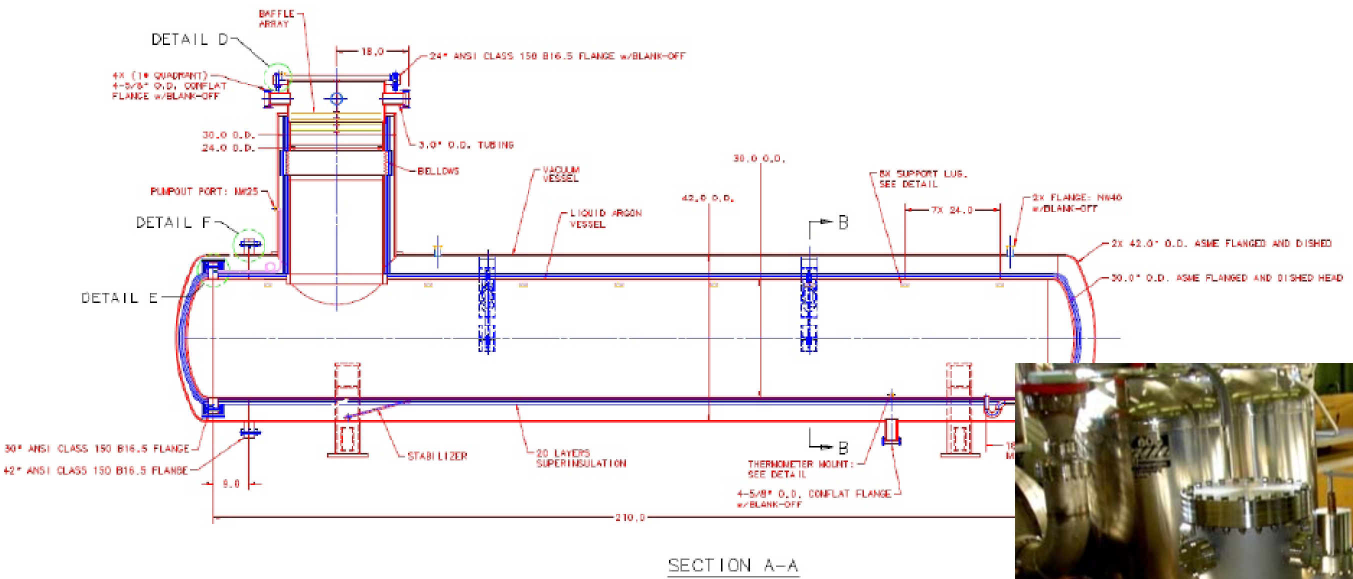
Measured Performance		
Impurity	Inlet	Outlet
O_2	0.4 ppm	<0.1 ppb
H_2O		<0.2 ppb
N_2	2 ppm	<1 ppb
CH_4	1 ppm	<1 ppb
CO		<0.5 ppb
CO_2		<0.1 ppb

Initial Hardware R&D at Fermilab

setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly at Fermilab

Possible 5 m Drift Test at Fermilab

Cryostat drawing for purchasing department

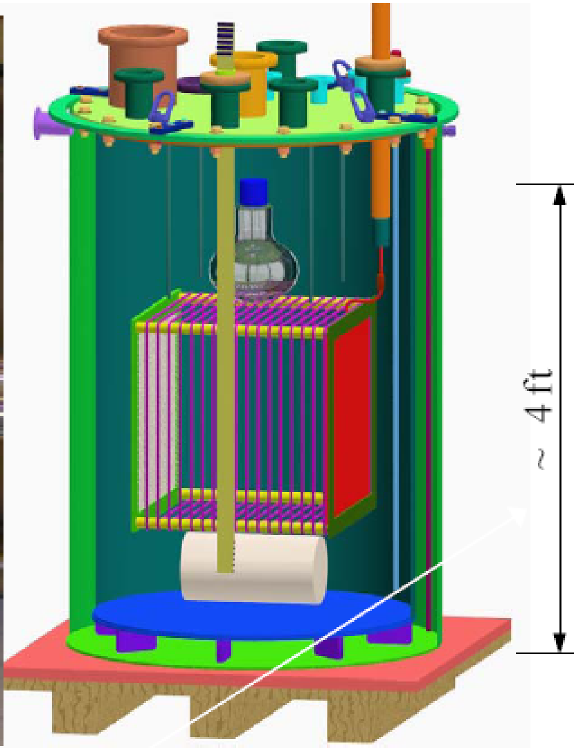


Complementary to UCLA/INFN
5 m drift test at CERN?
(F.Sergiampietri, et al.)

LAr TPC Test Setup @ Yale

(B. Fleming)

Purity monitor in liquid argon



Purity and light collection

R&D on Wire Stringing

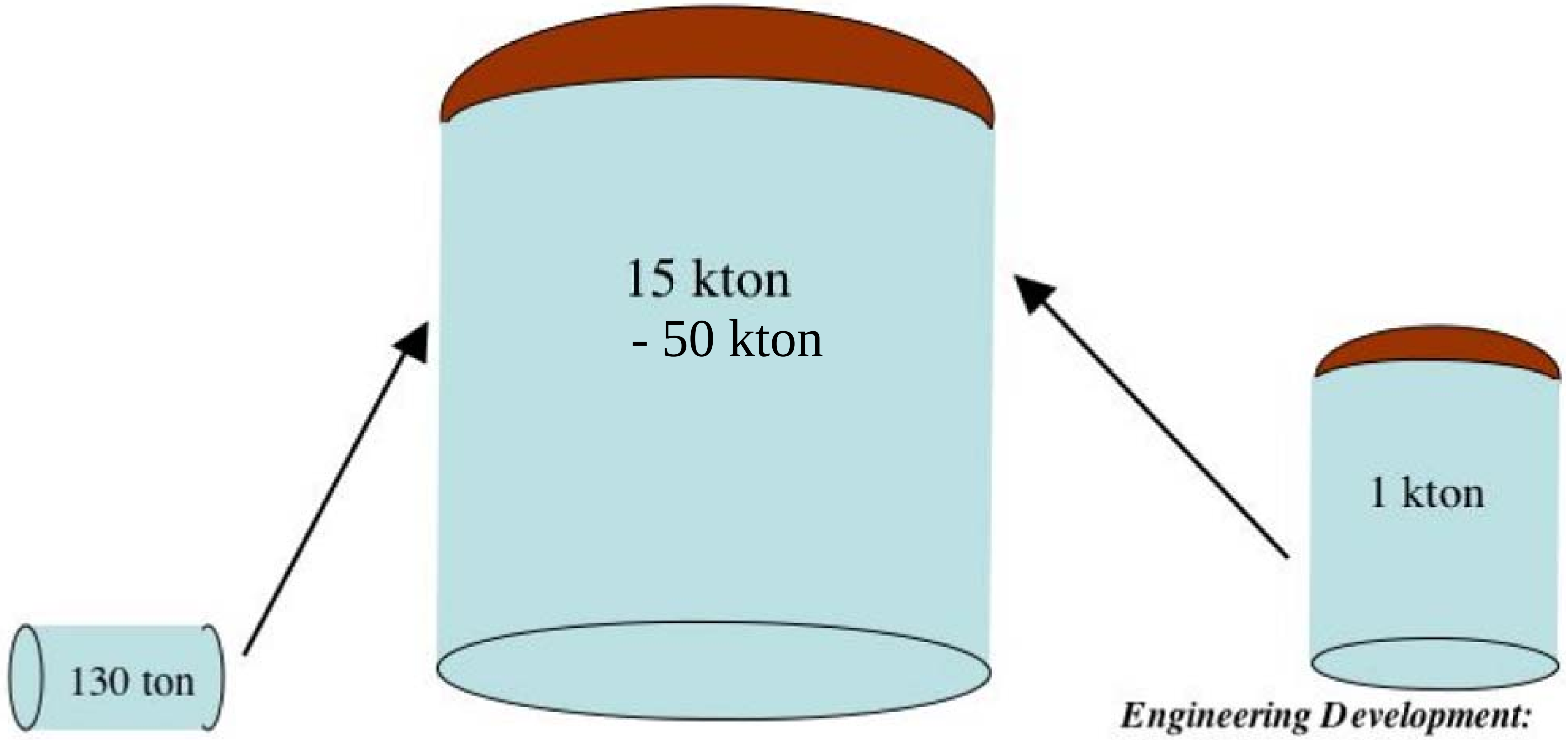
Systematic approach needed to learn how to string 100k's of wires.

- Potential cost driver.
- Mechanical robustness.
- Protection against consequences of wire breakage.

Where to do it?

- Lab E/F (~10 m height)
- D0 assy hall (~20 m)
- WH Atrium (30 m or more)

Longer Term R&D Towards 15~50 kT



Physics Development *using* ***existing*** *technology*
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**

Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow

Details of this program can be found in the document submitted by a US collaboration of "Liquid Argon Enthusiasts."

I am indebted to many of them for material I have used in this talk.

Fermilab Note: FN-0776-E

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam
Submission to NuSAG
September 2, 2005

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TPC Conclusions

- Large LAr TPC is a potential technology that could substantially extend our reach in neutrino physics.
- ICARUS provides proof that technology can work, but scaling it up to 10's kT mass appears prohibitively expensive.
- Ideas exist for much cheaper construction techniques, but these must be proven to work.
- R&D program is being launched at Fermilab and elsewhere to understand these ideas through engineering studies and hardware R&D.
- Most likely application would be for the next step beyond NOvA, e.g. detector at 2nd maximum.