Research and Development for Massive Liquid Argon TPCs (LArTPC) for Long-Baseline Neutrino Physics

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The discovery of neutrino mass in atmospheric and solar neutrino experiments, as confirmed in the K2K accelerator neutrino experiment and the Kamland reactor neutrino experiment, presents an opportunity for a full exploration of the physics of neutrino masses and mixing with long-baseline accelerator neutrino beams. Liquid Argon Time Projection Chambers (LArTPC) [1] are optimal detectors for this physics. Their fine-grained tracking capability, like that of bubble chambers of the past, combined with total-absorption calorimetry and scalability, make them natural candidates for large-scale, precision neutrino detectors. The success of the ICARUS T600 ($\sim$ 600 ton) program shows that these detectors are technically feasible on a "small" scale [3]. Building these detectors on a scale suitable for long-baseline, low-energy neutrino experiments requires additional R&D.

Construction of a $\sim$ 1-3-kton prototype TPC using technologies of the liquefied natural gas industry is a crucial step in the program *en route* to realization of a massive LAr detector. This prototype could be constructed on the surface at Fermilab to observe neutrino interactions from the NuMI beam or Booster Neutrino Beam (BNB)

A suitable level of funding for R&D on a 1-kton prototype liquid-argon time-projection chamber is $6M over 4 years; a 3-kton prototype would need funding of $13M.

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1 An R&D Program for a Massive LArTPC Detector

The use of liquid argon as a medium in an imaging detector is now a proven technique. This idea has been developed from the original proposals and modest test setups of some 20 years ago [1, 2] to the large multi-ton devices of the ICARUS collaboration [3]. These detectors are optimal for electron-neutrino appearance experiments as the efficiency for detecting ν_e's in a LArTPC is ~80-90% . This is a substantial improvement from a ~25% ν_e efficiency in conventional water Čerenkov or liquid scintillator detectors. In addition, the largest background, from neutral-current π^0 interactions, is reduced from the size of the intrinsic ν_e background in conventional experiments to a negligible level in LArTPCs.

The sensitivity of these detectors, described in [4] and [5], motivates an R&D program *en route* to realization of massive detectors. This R&D program is sketched in Figure 1 and consists of three main components, addressed by a collaboration of University groups and the Fermilab group.

1. A number of technical test set-ups directed to answering specific questions pertaining to a massive LArTPC (Fermilab focus).

2. The construction of a $\sim$ 30-ton fiducial mass ($\sim$ 100-ton total argon mass) detector in which interactions can be fully reconstructed. This detector will be placed in the halo of the NuMI and/or Booster Neutrino beams, where it can collect $\sim 10^3$ ν_e (and $\sim 10^4$ ν_μ) interactions in the energy range 0.5-2 GeV (University focus).

3. The construction and partial outfitting of a commercial tank of $\sim$ 1-3-kton capacity using the same techniques as proposed for the 15-100-kton detectors. This will serve as the test-bed to understand the issues of industrial construction (entire Collaboration).

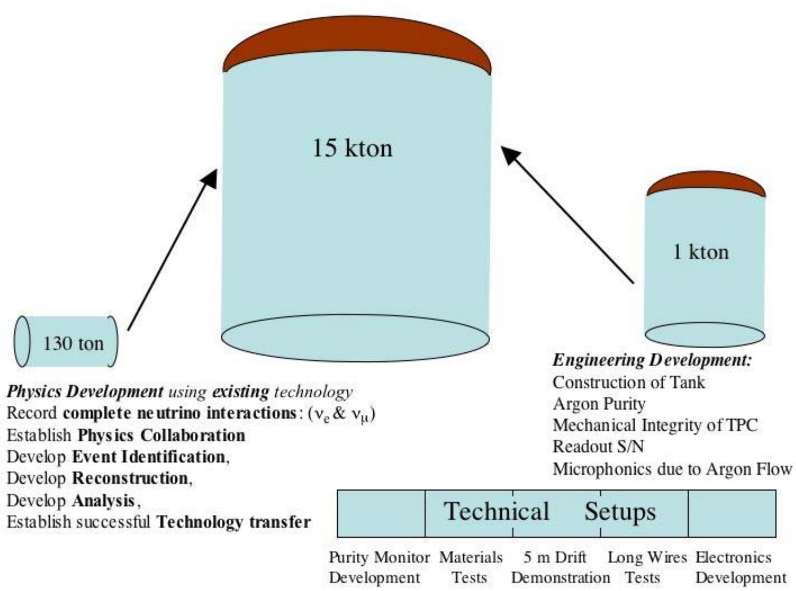

Figure 1: Scheme [4] of the LArTPC R&D program, including the $\sim$ 1-3-kton protoytpe.

2 The $\sim$ 100-Ton Prototype

A sketch of the $\sim$ 100-ton prototype is shown in Figure 2. It consists of an instrumented cylindrical volume of 7 m length and 2.1 m diameter, with outer dimensions of approximately 10 m $\times$ 3.0 m in diameter. This geometry realizes a fiducial mass of $\sim$ 30 tons.

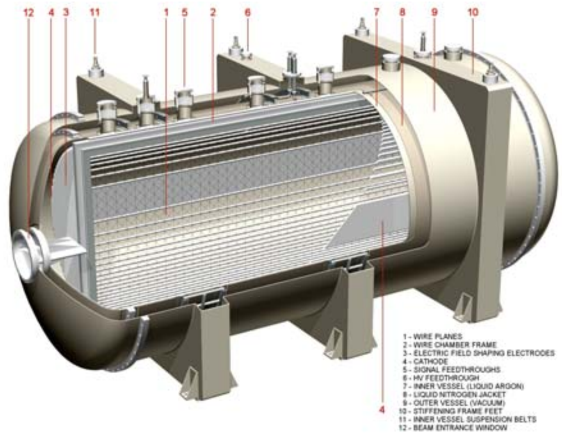

Figure 2: Schematic of cryostat and inner TPC of the $\sim$ 100-ton prototype [6].

While this detector is sizable, it is still small enough that it can be constructed by the University groups and transported via wide-load truck to Fermilab upon completion. A sample of ν_e and ν_μ interactions on the order of 1,000 and 10,000 events, respectively, can be collected in 1-2 years of operation in the the large-angle halo of the NuMI and/or Booster Neutrino beamlines [4]. These events, together with the cosmic-ray events that will also be collected, will form a very valuable sample on which the electronics, data acquisition, and analysis software for a LArTPC can be optimized.

With design and prototype work in FY2006, cryostat and TPC construction in FY2007, and installation in FY2008, data taking could begin in late 2008. The budget estimate for the $\sim$ 100-ton prototype is \$2M. An Expression of Interest for this phase only of liquid-argon detector R&D has recently been submitted to the Department of Energy [7].

3 The $\sim$ 1-3-Kton Prototype

The technology of relatively small liquid-argon detectors such as the $\sim$ 100-ton prototype or the ICARUS T600 module is not readily scaled to tens of kilotons in a cost effective manner. The key issue is the cryogenic system.

The liquefied-natural-gas industry has been constructing very large cryogenic storage tanks of volumes up to 200,000 m^3 for the past 60 years, which can be readily modified for use with a liquid-argon TPC (Fig. 3). Based on preliminary quotations from industry for delivery of large quantities of liquid argon, for construction of large cryogenic storage tanks, and for appropriate on-site liquid-argon purifications systems a scaling law for the cost of large liquid-argon detectors of mass M was devised [8]:

$$\text{Cost} \approx 1.33 \left[\$80M \ \left(\frac{M}{100\ \text{kton}} \right) + \$70M \left(\frac{M}{100\ \text{kton}} \right)^{2/3} \right].$$

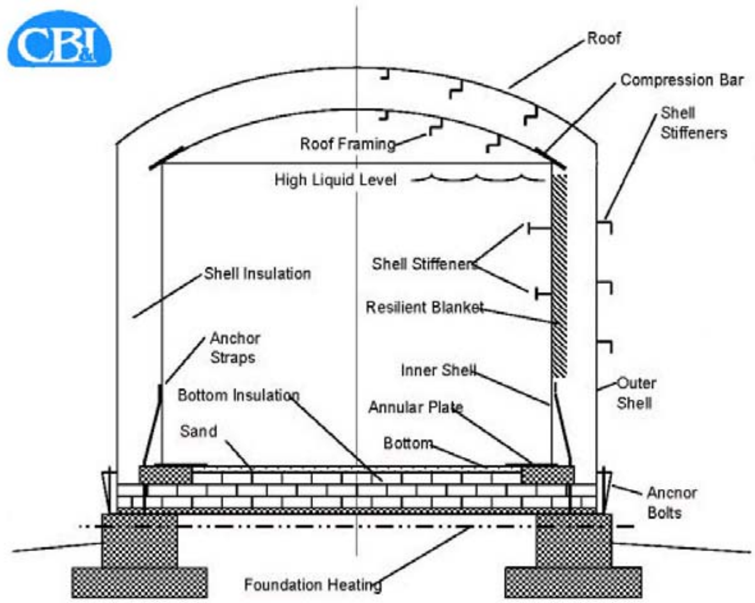

Figure 3: Sketch of a large cryogenic tank designed to contain a liquid-argon TPC (Chicago Bridge and Iron).

To take advantage of the relatively low costs represented by the above scaling law, the community needs to gain experience with several technical issues:

- Construction of a large cryogenic storage tank at a site suitable for a neutrino-physics detector.
- Cleaning of the interior of the tank sufficiently well to permit liquid-argon purity to be better than 0.1 ppb (as needed for electron drifts of several meters).
- Purging of nitrogen and oxygen without evacuating the tank (which is not a vacuum vessel).
- Construction of an on-site argon purification system that operates in the liquid phase.
- Construction of the TPC electrode structure inside a tank with only small accessways to the exterior.
- Fabrication and operation of a set of electrical feedthroughs compatible with the construction of the industrial cryogenic storage tank.

To address these issue an R&D program should be initiated. The goal is to be able to start construction of a liquid-argon TPC of mass 15-100 kton upon successful completion of the R&D. If we suppose that an extrapolation of linear dimensions by a factor of 3 is a plausible step from R&D to a physics detector, the mass of the industrial R&D prototype detector should be 1-3 kton.

Here, we provide a very preliminary cost estimate for an R&D program for a 1-kton prototype (Table 1), whose overall cost of \$6M is consistent with the scaling law given above. A 3-kton prototype would cost about \$13M at the present accuracy of estimation.

Liquid Argon TPC R&D Cost Estimate
(In thousands of US \$ (FY06))

1-kton neutrino detector prototype		
Cryostat and TPC Design	1500	
Liquid Argon Inventory	1500	
Engineering	400	
Cryogenic Equipment	400	
Wire Chamber, Field Cage	300	
Electronics (3000 wires)	200	
Feedthrough (HV/Signal)	100	
Software and Computers	100	
Sub-total		4500
Contingency		1500
Total		**6000**

Table 1: Breakdown of preliminary costing for a 1-kton LArTPC R&D program. Operational costs are not shown. A similar estimate for a 3-kton prototype detector is \$13M.

The R&D program sketched above involes only partial instrumentation of the detector. Construction of a full set of electrodes, with corresponding readout electronics would add about 10% to the project cost.

If appropriate funding is available, this program could be accomplished in 3-4 years.

This R&D program would also allow a physics collaboration to coalesce (including possible collaboration with ICARUS groups), students to be trained, and the North American groups to demonstrate our own hands-on mastery of the technology of liquid-argon time-projection chambers, while advancing this technology beyond the present state of the art.

4 Liquid Argon Detectors for DUSEL

Very large liquid-argon detectors are well suited for operation at a surface site with a pulsed, long-baseline accelerator neutrino beam. However, use of a $\sim$ 100-kton liquid-argon detector at an underground site would add a significant capability to observe proton decay via modes such as $p \to K^+\nu$ for which the efficiency of water Čerenkov detectors is very low. A Letter of Intent to explore this opportunity has recently been submitted to the DUSEL process [9]. We are continuing to develop R&D plans appropriate to this larger spectrum of physics opportunities for large liquid-argon detectors.

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