DUSEL R&D Proposal, Liquid Argon Purity Demonstration

Program announcement title : **DUSEL R&D Proposals in FY2008**
http://www.science.doe.gov/hep/DUSELR&D.shtm
Name of laboratory : **Fermi National Accelerator Laboratory**
Name of principal investigator (PI) : **David Finley**
Position title of PI : **Scientist II, Fermilab**
Mailing address of PI : **M.S. 122, PO Box 500, Fermilab, Batavia, IL 60510**
Telephone of PI : **630-840-4620**
Fax number of PI : **630-840-3614**
Electronic mail address of PI : finley@fnal.gov
Name of official signing for laboratory* : **Pier Oddone**
Title of official : **Director of Fermilab**
Fax number of official : **630-840-2900**
Telephone of official : **630-840-3211**
Electronic mail address of official : pjoddone@fnal.gov
Requested funding : **One year of funds are requested totaling $334,950**
Use of human subjects in proposed project : **No**
Use of vertebrate animals in proposed project : **No**

Signature of PI, date of signature

David Finley 12/3/07

Signature of official, date of signature*

Pierman Oddone 12/3/07

*The signature certifies that personnel and facilities are available as stated in the proposal, if the project is funded.

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(04-93)
All Other Editions Are Obsolete

U.S. Department of Energy

Budget Page

(See reverse for Instructions)

OMB Control No.
1910-1400
OMB Burden Disclosure
Statement on Reverse

ORGANIZATION Fermilab				**Budget Page No:**	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR David Finley				Requested Duration: (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested by Applpicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1.					
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)				0.00	0.00
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				0.00	0.00
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				0.00	0.00
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				0.00	
2. FOREIGN				0.00	
TOTAL TRAVEL				0.00	0.00
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				0.00	0.00
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				290,000.00	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				290,000.00	0.00
H. TOTAL DIRECT COSTS (A THROUGH G)				290,000.00	0.00
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 1.5% on subcontracts + 15.5% on M&S					
TOTAL INDIRECT COSTS				44,950.00	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				334,950.00	0.00
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				334,950.00	0.00

2.2 Budget Explanation

Fermilab will provide the scientific and engineering effort as well as the technical labor required to carry out the project. This proposal requests funds for materials and services (direct costs) to carry out the project. These costs are based on vendor quotes and catalog prices where possible, or experience with other similar scale efforts when a quote or price is not available. The resulting direct cost for the project (no labor and no overhead) is:

Item	Cost
Tank	$45k
Purification	$120k
Installation	$15k
Argon (3 fills)	$60k
Instrumentation	$50k

Thus the total direct cost is $290k. The total request shown in the Budget Form includes 15.5% laboratory overhead.

The tank will use the same fabrication techniques as appropriate for a large detector in regards to the liquid argon itself. It will be built by industry using techniques appropriate for a large tank, such as a flat bottom. It will have a single containment vessel rather than being double sided (since the argon only sees the inner surfaces). Because this is a temporary setup, we will use foam insulation on the sides and top and insulating bricks on the bottom. It has penetrations for installing equipment and for personnel access. The purification includes filtration materials, pumps, valves, plumbing and controls required for the four steps of purification for a large detector as described in this proposal. The installation includes material and service costs associated with initially rigging the tank to its location, cleaning the tank, welding the tank shut to start phase one, opening the tank and welding it shut again to start phase two. The argon cost is scaled from $1,000,000 per kilo-ton. The instrumentation includes purchase of parts for purity monitors, temperature gauges, flow meters, data monitoring devices and acquisition.

This request does not include costs that the laboratory would normally bear to clean out a hall to install the project, and the cost of disposing of the equipment after the project is complete. The laboratory will pick up the costs associated with publication of the results and travel to present the results at the appropriate venues.

Once the funds are available, and the resources and personnel are identified in the laboratory to do the work, the project should finish (i.e., have results on the achievable liquid argon purity without evacuation) within 12 months.

3 Abstract page

DUSEL R&D Proposal, Liquid Argon Purity Demonstration

Program Announcement Number : LAB 08
Program Announcement Title : DUSEL R&D Proposals in FY2008

Principal Investigator :
David Finley
Email: finley@fnal.gov
M.S. 122, P.O. Box 500
Fermi National Accelerator Laboratory
Batavia, IL 60510

Collaborating Investigators:
Fermi National Laboratory: Richard Schmitt, Stephen Pordes, Hans Jostlein, Doug Jensen, Regina Rameika

DUSEL could be the location of a large liquid argon time projection chamber (LArTPC) detector, but only if outstanding questions related to such a detector can be resolved. A crucial design feature of massive (multi-kiloton) liquid argon detectors for neutrino experiments (and other physics such as proton decay) is that the main cryogenic vessel is not evacuable. The cost of making a multi-kiloton capacity tank strong enough to sustain a vacuum is prohibitive. Achieving adequate argon purity in a large tank without evacuation has never been demonstrated and one cannot sensibly imagine investing in a multi-kiloton liquid argon detector without a demonstration that adequate purity can be obtained.

We propose here a minimal apparatus to make an effective demonstration of the ability to achieve purity. To reduce costs, the argon vessel is a single-wall vessel fabricated off-site and brought to Fermilab by truck. This allows an argon content of 20 tons (15 cubic meters). The tank is foam insulated and instrumented with temperature and flow gauges, and electron drift-lifetime monitors. The system for initial purging from atmosphere and then physical and chemical removal of oxygen is the same as we are considering for use on a multi-kiloton detector. The materials of a TPC can be placed in the tank but there is no plan to construct a functioning device as part of this purity demonstration. Of course, this project benefits from Fermilab's extensive cryogenic expertise and from the fact that there is space at the laboratory to install such a device.

We believe that this project addresses a clear potential show-stopper for the entire large liquid argon detector effort. Achieving adequate purity in this demonstration will be a tremendous boost to the credibility of proposals for multi-kiloton liquid argon detectors.

4 Narrative

4.1 Introduction

DUSEL could be the location of a large liquid argon time projection chamber detector, but only if outstanding questions related to such a LArTPC detector can be resolved. This proposal addresses one critical, outstanding question: What is the feasibility of achieving the required liquid argon purity without evacuating the cryostat containing the TPC? In addition, one must understand the purification costs, both in money and time, of implementing a successful purification technique on a large LArTPC. The project proposed here will do both of these.

To be at DUSEL on the physics frontier of neutrino oscillations or proton decay one must consider a total detector mass on the 100 kiloton scale. To date, all LArTPCs have utilized cryostats which are evacuated after the TPC itself is located inside it. If it were contained in an upright cylinder, the volume required for 100 ktons of liquid argon (with density 1.4 grams per cubic centimeter) would be about 45 meters diameter and 45 meters height. It is not thought to be sensible to consider evacuating any kind of detector of this size, especially in an underground cavern. The cost of constructing the walls of the containment vessel to prevent collapse is thought to be prohibitively expensive. It is obviously sensible to avoid personnel safety issues related to collapse of such a vessel simply by avoiding the requirement on evacuation in the design.

In addition, any LArTPC has a special requirement: achieving and maintaining an acceptably low level of electronegative contamination (such as oxygen). For a large LArTPC at DUSEL, the required purity is a few tens of parts per trillion oxygen equivalent. This level will allow a sufficient fraction of the electrons, which are ionized from argon atoms by charged particles of interest, to survive a drift of several meters in the applied electric field. As a specific example, 30 parts per trillion oxygen equivalent contamination corresponds to a 10 millisecond electron drift lifetime. For the applied electric field we are considering, electrons take 2 milliseconds to drift 3 meters. Thus, in this specific example, there would be an average electron loss of 10%, and a maximum loss of 20%.

ICARUS T600 (S. Amerio et.al., NIM A527 (2004)) is the largest LArTPC to date and it has demonstrated the liquid argon TPC technique can be made to work, once the purity is achieved. T600 is composed of two 300 ton detectors inside cryostats which are evacuated. Using evacuated units of approximately this size to achieve 100 kilotons may not be impossible, but it is recognized to be quite expensive.

A 100 kiloton detector is an appropriate goal for DUSEL, and this may or may not be achieved in a single unit. For example, one could consider two 50 kiloton devices if the cavern construction would not accommodate the diameter of a single detector. Or one can consider smaller devices, perhaps 10 to 20 times less massive, in the range of 5 kilotons to 10 kilotons. Devices of just this size are being considered for neutrino oscillation physics using off-axis experiments utilizing existing neutrino beam lines (the NuMI line from Fermilab to Minnesota or the CNGS line from CERN to the LNGS in central Italy). If contained in

upright cylinders, a 10 kiloton detector would be about 22 meters in diameter and 20 meters in height, and a 5 kiloton detector would be about 18 meters in diameter and 15 meters in height. A detector of this scale would be recognized as a true prototype of the large detector if constructed with the same techniques as the large detector. On the other hand, some think an even smaller scale, 1 kiloton or less, should be the appropriate size for the next detector. An additional crucial goal of the smaller detectors would be to demonstrate one can do physics experiments using detectors which have not been evacuated. Any of these efforts requires demonstrating the feasibility of achieving the required purity without evacuation, at a reasonable cost, as proposed here.

In order for the demonstration to be as relevant as possible, it is important that we provide the argon the same experience it will encounter in a very large detector. Thus the materials, fabrication techniques, and cleaning techniques of the tank itself must be as similar as possible to that to be used by a large detector. The size we have chosen for the demonstration will hold 20 tons of liquid argon. This size was chosen to be as large as possible and still be transportable from the industrial shop in which it will be constructed.

4.2 Four Purification Steps

We will use four steps of purification: Initial purge from atmosphere, gas purification, filtration of liquid argon, and liquid purification. An engineering drawing of the tank is in the Appendix and is also available at http://lartpc-docdb.fnal.gov/0003/000318/001/LAR_PURITY_DEMO_VESSEL.pdf .

The initial purge from atmosphere will be done taking advantage of the fact that argon gas is heavier than air. We will introduce argon gas at the bottom of the tank at a rate that preserves a reasonably distinct boundary between the argon gas and the gas above it. Initially the gas above is pure air and it is pushed out of the tank through an outlet at the top of the tank. The gas boundary between the argon gas below and the gas above is not perfect because some diffusion between the gasses does occur. However, we have demonstrated the gas boundary can remain rather distinct in the case of a much smaller tank as reported in Fermilab TM 2384-E, available at http://lss.fnal.gov/archive/test-tm/2000/fermilab-tm-2384-e.pdf . The key is to introduce the argon slow enough to avoid mixing. In this much smaller tank, after only a few volume changes, the gas purity in the tank reached a level appropriate for about ten volume changes for the case of perfect mixing. Of course, one can choose to flow the argon gas fast enough to approach perfect mixing. However, the total argon cost used in this step in a large tank should be about three times less using this gas boundary technique for the initial purge. The rate at which the gas is introduced will be the same as anticipated in the large LArTPC detector so the gas dynamics are as similar as possible, and thus we can understand how the cost scales.

The second step is to purify the argon gas. For this step, the tank outlet is sealed, and the argon gas is recirculated through an external filtration system. At the end of this stage the gas must reach the same level of purity as one achieves after introducing argon into an evacuated cryostat. The filtration system used will be scaled down from what would be used in a large LArTPC detector so the costs can be understood.

The third step is to introduce liquid argon from tanker trucks and pass it through a single pass filtration system directly to the tank. This filtration system is based on the one we have used at Fermilab to achieve the required liquid argon, but it is scaled down from what would be required in a 100 kiloton detector. We intend to demonstrate that the initial level of liquid purity can be achieved, and use this experience to scale to the purification cost to the large detector. (See section 6.2 for the method we use to measure liquid argon purity.) The fourth step of purification is to maintain the purity achieved in the previous step. We intend to use the same filtration equipment as in the previous step.

4.3 Two Demonstration Stages

In the first stage we will use a tank without TPC materials in it. We want to determine whether the required purity can be achieved in a minimally equipped bare metal tank by starting from atmosphere (and not evacuating) using the four steps. The minimally equipped tank will have several items in it: purity monitors, temperature and flow monitors distributed throughout the volume, and the gas distribution system at the bottom.

To prepare for the second stage, we will remove the liquid, return the tank to room temperature, and open it up to atmosphere. Then we will use the port at the top of the tank to introduce materials which are appropriate for a fully functioning TPC. And then we will perform the four purification steps again. This stage is intended to directly address the issue of whether the process of evacuation removes electronegative contaminants from these materials. We are studying this issue at our Material Test Station as described in Section 6.1.

We have allowed for three complete liquid argon fills of the tank in the budget. Two of them are for the two stages outlined above. We anticipate using an additional one learning how to do things correctly.

4.4 Features Not Included in This Proposal

We choose not to have a functioning TPC because the TPC technology has been shown to work in liquid argon (once the required purity is achieved). We choose not to introduce penetrations into the tank which would be used to connect the TPC to outside the tank. It is important that these penetrations be done properly, but it has already been demonstrated that they can be done. We choose not to introduce these features in the demonstration project in order to keep the focus on the feasibility of achieving the purity, and to save money.

Once the project is complete, and if we demonstrate we can get the purity required without evacuating the detector, the tank will be available for further R&D not included in this project. For example, one may very much wish to put a functioning TPC in the tank and install it in a beam line. This would require some modifications to the tank, such as providing feed-throughs for high voltage and readout of the TPC wires, and rearrangement of the instrumentation used for this project. In addition, one may wish to provide more robust (and perhaps more expensive) thermal insulation.

5 Biographical Sketches

5.1 Investigator Biographical Sketch

David A. Finley
Fermi National Accelerator Laboratory
Telephone: 630-840-4620
Email: finley@fnal.gov

Professional Preparation:

Purdue University Physics Bachelor of Science, 1970
Purdue University Physics Master of Science, 1972
US Army Officer 2nd Lieutenant, 1972-1974
U.S. Army Harry Diamond Laboratories, Washington D.C.
Purdue University Physics PhD, 1978

Research Associate 1978-1981
State University of New York at Stony Brook, on E605 at Fermilab
Associate Scientist, Fermilab 1981-1984
Head, Switchyard Group, 1981-1984
Scientist I, Fermilab 1984-1990
Head, Tevatron Group, 1989-1990
Scientist II, Fermilab 1990-present
Head, Main Accelerator Department, 1990-1991
Associate Head, Accelerator Division, 1991-1992
Deputy Head, Accelerator Division, 1992-1994
Head, Accelerator Division, 1994-1996
Head, Beams Division, 1996-1998
Accelerator R&D, 1998-2005
Lead Scientist, Linear Collider R&D, 2001-2005
Member of MiniBooNE Collaboration, 2003-present
Lead Scientist, LArTPC R&D, 2005-present
Member of SciBooNE Collaboration, 2006-present

Publications relevant to this proposal:

- "Recent Progress in Neutrino Factory and Muon Collider Research Within the Muon Collaboration", by the Muon Collider/Neutrino Factory Collaboration with M. M. Alsharoa et al, Phys.Rev.ST Accel.Beams 6:081001, 2003; e-Print Archive: **hep-ex/0207031.**
- "A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-axis Neutrino Oscillation Physics with the NuMI beam", submitted to HEPAP/NuSAG, September 21, 2005, available at http://lss.fnal.gov/archive/test-fn/0000/fermilab-fn-0776-e.pdf .
- "Liquid Argon TPC Activities at Fermilab etc" presented at the September 2006 NNN06 workshop Seattle Washington, available at **http://lartpc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=211**

- “R&D for an Ash River LAr Detector”, presented at the Cryodet2 Workshop at LNGS 2007, http://cryodet.lngs.infn.it/agenda/CRYODET-2_agenda_fin.htm
- “Large Liquid Argon Detector R&D in the US”, presented at the October 2007 NNN07 workshop Hamamatsu Japan, available at http://lartpc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=313

Five Other Publications:

- "Nucleon-Number Dependence of Inclusive Dihadron Production in Proton-Nucleus Collisions at 400 GeV/c," D. A. Finley, et al., Physical Review Letters, 42, 1031 (1979).
- "Fermilab Collider: Performance and Plans," David A. Finley, Proceedings of the International Europhysics Conference on High Energy Physics, Marseilles, France, July 1993.
- “Compensation of Beam-Beam Effects in the Tevatron with Electron Beams”, V. Shiltsev, V. Danilov, D. Finley, and A. Sery, Phys. Rev. ST Accel. Beams 2, Number 7 (July 1999).
- “Search for Electron Neutrino Appearance at the Δm^2~1 eV^2 Scale”, A. A. Aguilar-Arevalo et al. (for the MiniBooNE Collaboration), Phys. Rev. Lett. 98, 231801 (2007) also available at e-Print Archive http://arxiv.org/abs/0704.1500

Synergistic Activities:

- Member of the Muon Collider and Neutrino Factory advisory committee (2006-present)

Collaborators: Richard Schmitt, Stephen Pordes, Hans Jostlein, Doug Jensen, Regina Rameika (Fermilab)

Graduate Advisors: Kenneth Stanfield and Edward Shibata (Purdue University)

6 Facilities and Resources

6.1 Fermilab Facilities

Fermilab has more than one place where this project can be done, and it has the mechanical, electrical, cryogenic, and networking infrastructure to carry out the project. We have designed the tank so that it can be delivered to and located inside the KTeV Hall, which is not used for fixed target experiments at this time. If located here, it will be necessary to move equipment from the completed experiment to make room for this project, and Fermilab would pay for this. Locating the demonstration in this particular hall allows us to use the existing crane to move the tank, and thus save costs.

Much of the ongoing R&D on LArTPCs at Fermilab is taking place inside the Proton Assembly Building (PAB). Of particular note for this project, the Materials Test Station began final commissioning in November 2007 (See Photo 1.) The purpose of this facility is to study (a) the contamination of liquid argon by various materials and (b) the efficacy of various 'filters' for the removal of oxygen (and other electronegative species). This facility provides a closed system which uses a condenser to return boil off argon gas to the liquid volume and an internal filter to clean the liquid argon. It provides a "materials lock", which is isolated from the gas above the liquid by an isolation valve, into which one can insert materials into a small cage (15 cm diameter by 25 cm height). One can then choose to evacuate the materials lock, or purge it with clean argon from the gas above the liquid, and then insert the materials contained in the cage into the liquid after opening the isolation valve. After measuring the effect on the drift lifetime, one can characterize the appropriateness of the material (and its preparation) for use in a LArTPC. If the material contaminates the liquid, the in-situ filter can remove the contaminants after the material is moved back into the materials lock, and the isolation valve is closed. These tests are part of the ongoing purity effort at Fermilab. (For additional details, see http://lartpc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=313 .)

6.2 Fermilab Resources

To measure the purity of the liquid argon, we will use the purity monitors based on those developed for use in ICARUS (G. Carugno et. al., NIM A 292 (1990)). Details of the specific implementation at Fermilab may be found in Fermilab TM 2385-E, available at http://lss.fnal.gov/archive/test-tm/2000/fermilab-tm-2385-e.pdf . Photo 2 shows the signals obtained in February 2006 from a purity monitor fabricated at Fermilab. Analysis of these signals demonstrated we can indeed achieve the liquid argon purity, albeit a very small scale, required for a large LArTPC.

Fermilab has extensive expertise with personnel safety issues related to cryogenics. The lab has developed appropriate procedures and reviews to assure work as described here is done safely.

Photo 1. Proton Assembly Building at Fermilab showing the Materials Test Station in August 2007.

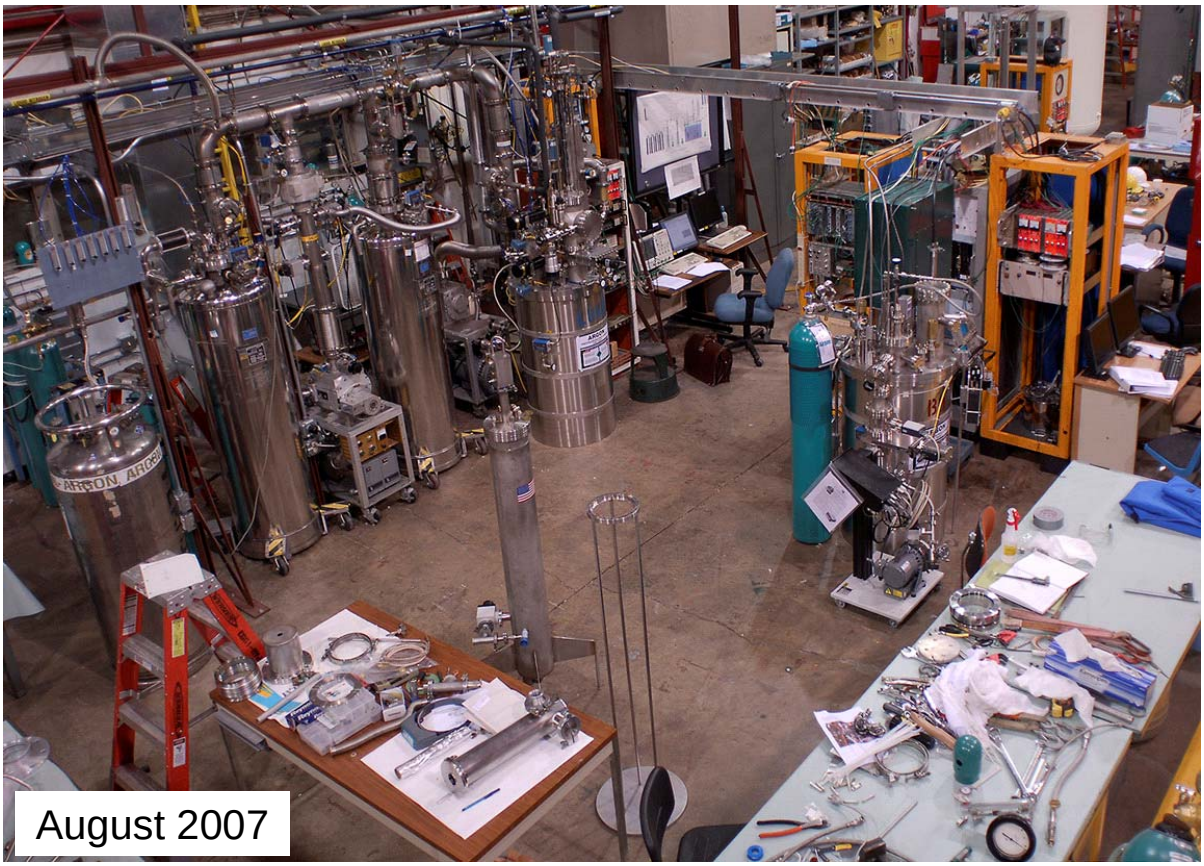
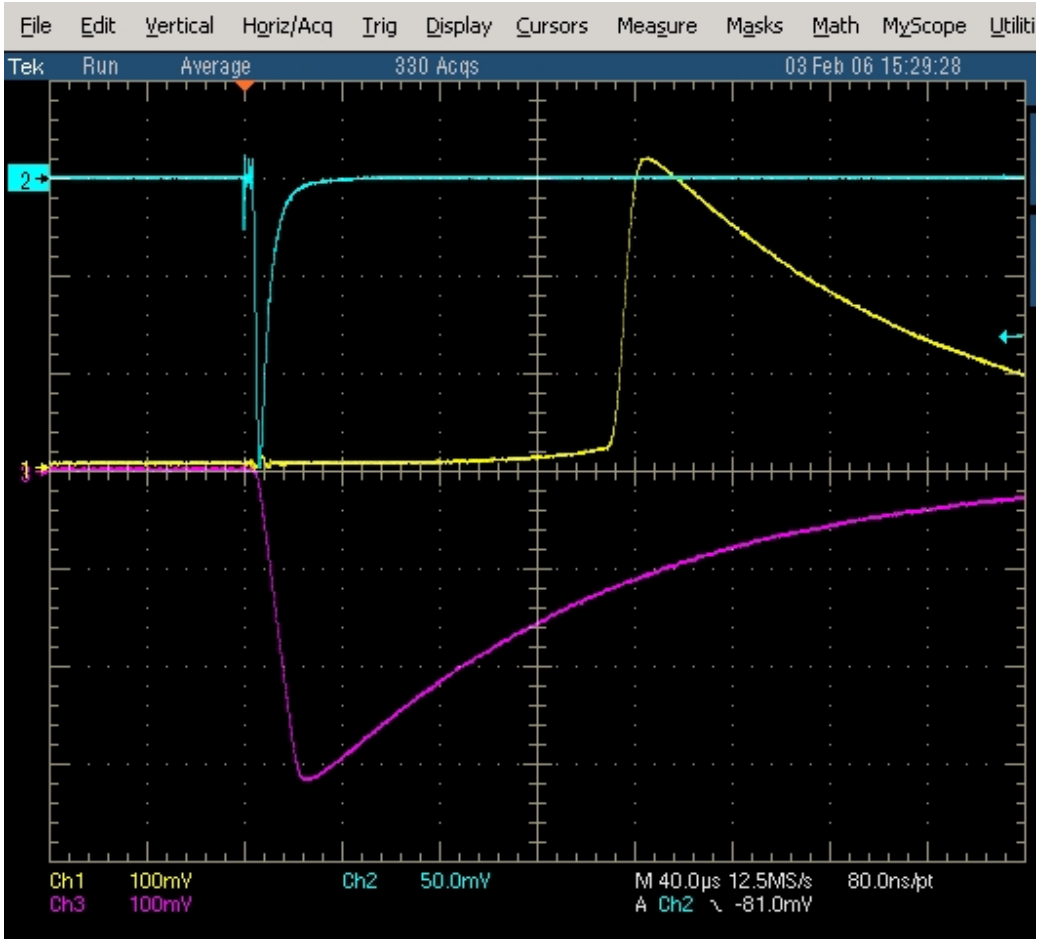


Photo 2. Signals from Purity Monitor on February 6, 2006.



7 Other Support

7.1 Fermilab personnel

Here are brief, relevant statements regarding the Fermilab collaborators named in the biographical sketch of the PI.

Richard Schmitt, Engineer IV, joined Fermilab 1985
Bachelor of Mechanical Engineering 1973 from University of Illinois in Urbana
33 years of cryogenic engineering experience
Design of liquefied gas storage and space simulation chambers
Design and operation of thermal processes
Head, Process Engineering, Mechanical Department of the Particle Physics Division

Hans Jostlein, Scientist II, joined Fermilab 1975
Member of NOvA Collaboration
Active in liquid argon TPC R&D since 2003

Stephen Pordes, Scientist II, joined Fermilab 1980
Coordinator of liquid argon TPC R&D technical activities since 2004

Douglas Jensen, Scientist II, joined Fermilab 1990
Physics Faculty at Princeton and University of Massachusetts at Amherst
Member of NOvA Collaboration
Active in liquid argon TPC R&D since 2005

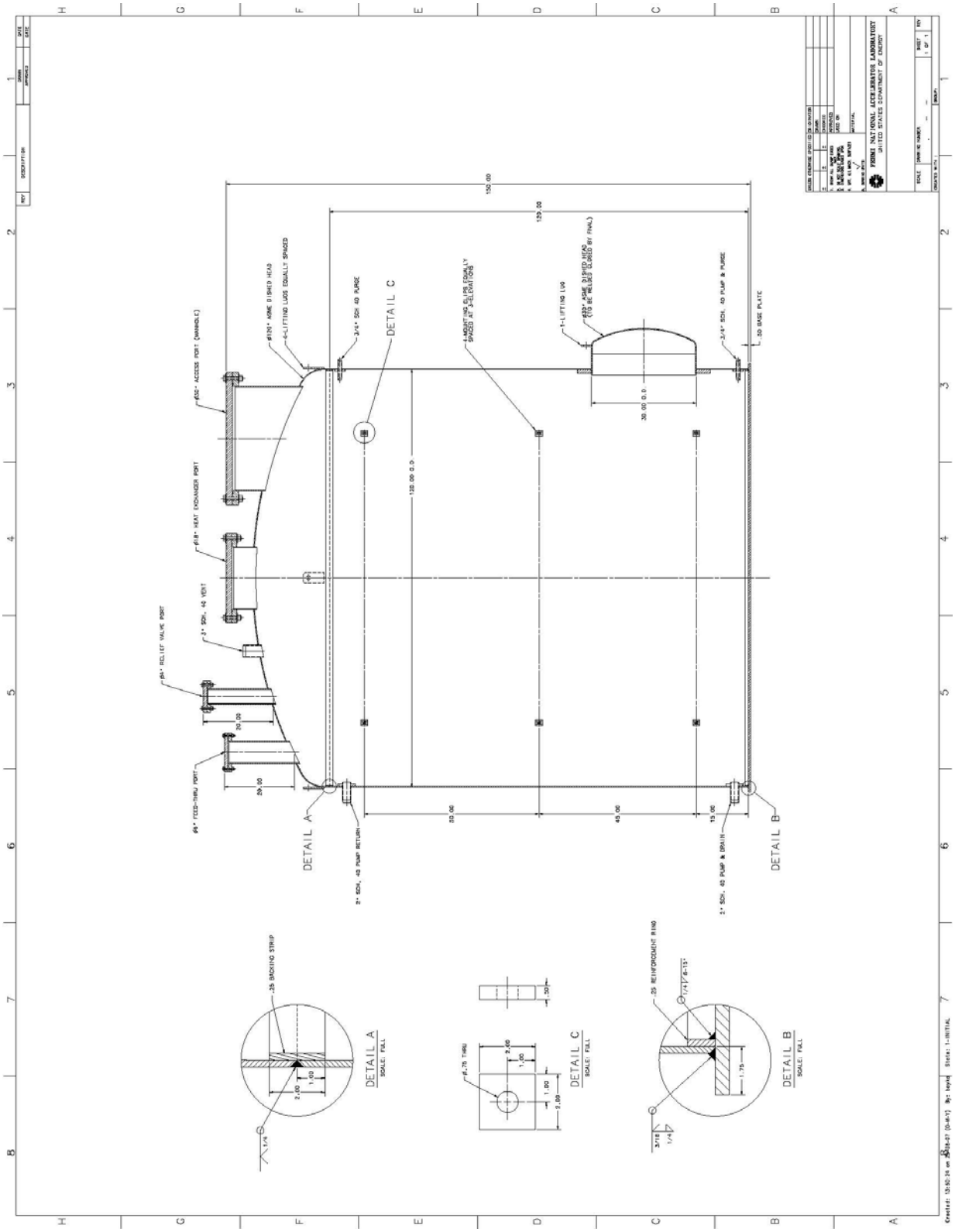
Regina Rameika, Scientist II, joined Fermilab 1982
Head of Neutrino Department in Particle Physics Division
Member of MINOS and NOvA
Co-author Long Baseline Study led by Fermilab and Brookhaven
Active in liquid argon TPC R&D since 2006

If the project is approved, it is likely other Fermilab people will contribute to the project.

7.2 Other personnel

At this time we are in communication with various other groups about this project, but we are not counting on them for material support at this time. However, it is likely some of them may become involved with the data taking, analysis and understanding of the result.

APPENDIX: Engineering Drawing of the tank



MICHIGAN STATE
UNIVERSITY

November 29, 2007

David Finley and Stephen Pordes
Fermilab, Batavia IL, 60510

Dear David and Stephen:

I am writing to support your proposal to find the achievable purity of 20 tons of liquid Argon in a commercial vessel that cannot be evacuated. I believe that this test is on the critical path leading to a practical Liquid Argon Time Projection Chamber (LArTPC) for future experiments. This test must be done as soon as possible to allow a large LArTPC to be considered for a neutrino experiment at Ash River, or a prototype proton decay detector at DUSEL.

For proton decay searches and neutrino oscillation studies, the best detector in terms of signal efficiency, background rejection, and (by estimation) the cost per kiloton of fiducial mass, is a large (5-50 kiloton) LArTPC. All existing detectors are much smaller, the largest being the ICARUS dual 0.3 kiloton detectors, and all have been evacuated to clean the vessel of electron lifetime reducing contaminants, such as water and oxygen.

However, the much larger cryogenic vessels needed for these studies cannot be evacuated. If large and expensive LArTPC detectors are to be supported with confidence, the required purity must be achieved in an inexpensive vessel of similar construction. Your proposal for a test of a 20 ton vessel, the largest that can be built off site (economically) and transported to Fermilab, will make (or break) the case for these detectors.

Best regards,

Carl

Carl Bromberg
Professor of Physics

Department of Physics & Astronomy
Michigan State University
East Lansing, Michigan
48824 – 2320

TEL: (517)355-9200 x 2122 E-mail: bromberg@pa.msu.edu
FAX: (517)355-6661

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