Fine Grained Scintillator Tracker as Candidate LBNE Near Detector

Robert Bradford
University of Rochester

Donna Naples, Vittorio Paolone
University of Pittsburgh

Jorge Morfin
Fermi National Accelerator Laboratory

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1 Introduction

The Near Detector group is currently considering a fine-grained scintillator tracker as a candidate near detector for LBNE. The heart of the proposed detector is a large tracking volume filled with fine-grained scintillator extrusions. Each scintillator has an embedded wavelength shifting fiber to facilitate collection of scintillation light, and every scintillator/WLS fiber channel is individually instrumented with a dedicated photosensor. This detector technology provides full event reconstruction, with high resolution tracking capabilities. It is also possible to build up regions of calorimetry by interspersing appropriate absorber material (steel or lead) between sheets of scintillator.

Extruded polystyrene scintillator is not a new concept that has been used successfully in many past experiments. The idea that fine-grained scintillator could be used for a precision tracking detector was first used at K2K in the SciBar near detector. In 2007-2008, SciBar was moved to the BooNE beam-line at Fermilab and ran as SciBooNE, which studied interaction issues and cross sections of interest to the T2K long baseline program. Fermilab made a significant investment in polystyrene scintillator with the construction of the MINOS experiment. Both the near and far detectors are sampling calorimeters whose active component is extruded polystyrene with a rectangular profile (1.0 cm x 4.1 cm in cross section). Fermilab has an existing extruder line capable of producing modest quantities of scintillator in custom profiles.

Fine-grained scintillator has been a popular choice for near-detector applications as demonstrated in the construction of two new detectors. MINERνAis a new experiment running in the NuMI beam-line, dedicated to studies of neutrino interactions. MINERνAfeatures a large tracking volume of fine-grained scintillator encased in electromagnetic and hadronic calorimetry. It boasts 3 mm vertex resolution and full event reconstruction across a broad kinematic range. Similarly, the T2K 280m near detector features a central tracking region (the P0d) constructed of the same scintillator that was used in MINERνA. As Super Kamiokande is the far detector for T2K, the 280m near detector features interspersed water targets. Scintillator for both experiments was produced on the Fermilab extruder line.

The overall plan for a fine-grained scintillator tracker for LBNE was to re-use large pieces of the MINERνAdetector. While the detector will need upgraded downstream hadronic calorimetry and photosensors, a re-configured MINERνAdetector is capable of meeting the near detector needs of LBNE for a modest cost of $10-15M.

This chapter, then will outline the conceptual plan of a fine-grained scintillator tracker for use as an LBNE near detector. Section 2 will detail the technical design of the detector, including a discussion of how MINERνAwill be reconfigured to meet the needs of LBNE. Section 3 will detail infrastructural and personnel needs required to deploy and operate the detector. The last two sections will discuss current R&D plans (Section 4) and the plan for safe implementation of the project (Section 5).

2 Technical Description

In its current incarnation, the MINERνAdetector is constructed of 120 planar structures called "modules". A typical module consists of two sheets of fine-grained scintillator mounted into a hexagonally shaped steel frame. While the steel frame provides the mechanical structure of the module, it is also instrumented and provides hadronic calorimetry for particles exiting out the side of the detector. A typical module contains 302 individually instrumented pieces of scintillator, is 1.5" thick, and weighs just over 3,000 pounds. Modules are hung sequentially on a stand to make up the detector, much as slices make up a loaf of bread. In the downstream regions of the detector, passive absorber material has been interspersed between sheets of scintillator to build up calorimetry regions. The downstream electromagnetic calorimeter is constructed of modules whose scintillator planes have been covered with 2mm-thick lead absorber. The downstream hadronic calorimeter contains modules having only one scintillator plane and a 1" thick steel plate. The very upstream region contains a variety of solid targets (carbon, iron, and lead) embedded in regions of tracking scintillator. The overall layout of the detector structure is shown in Figure **??**.

The modular construction of MINERνAalso makes the detector reconfigurable. This section discusses how we propose to reconfigure the MINERνAdetector to meet the needs of LBNE. We begin by explaining the physics needs motivating the design (Section 2.1), then give an overview of the reconfigured detector (Section **??**).

2.1 Philosophy of Reconfigured Detector

Chapter **??** of this document discusses the physics goals of the near detector program, including the need to sample the un-oscillated flavor content of the LBNE beam. Of particular interest is the ν_μ, anti-ν_{mu}, and ν_e content of the beam. While MINERνAis capable of identifying the lepton in CC final states, separation of ν and anti-ν final states is problematic with the current detector. As configured, MINERνAdoes not incorporate a magnetic field, so sign determination of the final state lepton is limited. Muons that do no range out in MINERνAmay pass downstream into the MINOS near detector, which is magnetized. The threshold for identifying the charge sign of a MINERνA-produced muon with the MINOS near detector is 1.2 GeV. In addition to the obvious kinematic threshold, acceptance for muons entering MINOS falls off for interactions originating in the more upstream regions of MINERνA.

Figure **??** shows simulated far-detector oscillation results for LBNE assuming various combinations of the mixing angles, CP violating phase, and sign of the mass hierarchy. In all cases, the oscillation spectrum has little structure below E_ν=500 MeV. In planning the detector, we wanted to ensure reasonable muon charge sign discrimination for low-E$_\nu$ events. Figure **??** shows the fractional energy distribution for muons produced in events having an incident neutrino energy of 500 MeV ¡ E$_\nu$ ¡ 1.0 GeV. We set a lower muon charge sign identification threshold in order to ensure reasonable determination of the anti-ν_μ content of the beam at E$_\nu$=500 MeV.

2.2 Detector Overview

Our proposed redesign is illustrated schematically in Figure **??**. In large part, the detector conserves the existing MINERνAtracking volume and downstream electromagnetic calorimeter. The solid

upstream nuclear targets will be removed and replaced with targets more appropriate for LBNE. The most dramatic change is a new downstream hadronic calorimeter. The new HCAL is magnetized and features steel absorber of graduated thicknesses. The following sections provide a few more details of each main detector subsystem.

2.2.1 Targets

In this detector, most of the interactions will occur on the polystyrene scintillator itself. However, other target material can be inserted in between modules, with final state particles being tracked in the surrounding scintillator. As the results of the fine-grained tracker will be most pertinent to a water Cerenkov far detector, water will be the most important target material.

At this point, the design of the water target remains a work in progress. One option is a passive volume of water. The T2K 280m Near Detector incorporates several thin layers of water contained in large plastic bladders. The bladders are distributed throughout the detector's tracking volume, with sheets of tracking scintillator separating target material. The relatively thin targets minimally disrupt the tracking volume. The bladders can be filled and emptied in place, permitting studies of event production on the empty target material. We could implement a similar scheme, perhaps using multi-cellular Lexan sheets.

Christopher Mauger is working on the design of active water targets for use in the near detector program. While the effort is just beginning, the basic idea would be to instrument the water itself, either in liquid form or by production of optical quality ice. Christopher's targets are described in Section **??**.

The exact design of the targets, the total volume of water, and its distribution in the tracking volume of the detector remain important issues to be studied.

2.2.2 Tracking Volume

We currently plan to use the existing tracking volume from MINERνA. In its current form, MINERνAdedicates 60 modules to an un-interrupted tracking volume absent of any passive material for targets or calorimetry. This volume encompasses 120 sheets of scintillator, for a total of 15,249 channels, and a total fiducial volume of approximately three tons.

2.2.3 Electromagnetic Calorimetry

This is another system we will keep in-tact from the current MINERνAdetector. The current electromagnetic calorimeter consists of 10 modules, each containing 2 sheets of scintillator. The upstream face of each scintillator plane is covered with a 2mm thick Pb sheet which serves as the calorimeter's absorber material. Distributed over 20 scintillator planes, there is a total thickness of 4 cm of Pb in the calorimeter.

2.2.4 Magnetized Hadronic Calorimeter

The downstream calorimeter is the fist of two major upgrades to the baseline MINERνAdetector. The existing calorimeter consists of 20 modules, each containing one scintillator plane and a 1"-thick steel plate. If the current calorimeter were magnetized, the absorber would be too thick to permit lower energy muons to penetrate sufficiently deep into the calorimeter to determine a track curvature, and the sign of the muon.

We are proposing to build a longer, magnetized hadronic calorimeter with graduated steel absorber. The graduated absorber facilitates charge discrimination of lower-energy muons by measuring the track curvature. The calorimeter will be based on the modular construction of MINERνA. The calorimeter modules will still feature a steel frame encasing one sheet of scintillator and a steel absorber plate. The baseline design calls for 15 modules having 1/4"-thick steel absorber, 15 modules

having 1/2"-thick absorber, and 15 modules having 1"-thick absorber. A 300 MeV muon originating in the downstream portion of the fiducial volume will be able to cross the first calorimeter region, which should permit determination of the muon's charge. The threshold for traversing the second region (1/2" steel) is approximately 600 MeV. Total energy deposit for a muon traversing the three regions is approximately 1.0 GeV. Muons not ranging out in the calorimeter will still have their charge measured in the hadronic calorimeter, and will pass into the downstream muon catcher for further analysis.

This calorimeter will require steel and extruded scintillator sufficient to produce thirty additional MINERνA-type calorimetry modules (We plan to re-use 15 of the existing calorimeter modules for the region with 1"-thick absorber.). The calorimeter's magnet will be discussed in Chapter **??**.

2.2.5 Downstream Muon Ranger

To further analyze muons passing through the upgraded hadronic calorimeter, we will employ a downstream muon ranger. Our current plan is to employ a subset of the MINOS Near Detector.

2.2.6 Photosensors and Electronics

Because of the calorimeter's magnetic field, we plan to replace MINERνA's Hamamatsu M-64 photomultiplier tubes. We will upgrade the photosensors to some kind of pixelated silicon photodiode, such as MPPCs or SiPMs. Silicon photodiodes are not affected by an ambient magnetic field. They also have the advantage that the higher quantum efficiency will help offset lower production of light from the scintillator as it ages. To simplify readout, we will also replace the old MINOS electronics in the Downstream Muon Ranger. The final detector will employ one single type of photosensor for all instrumented channels.

The upgraded photosensors will also require new front-end electronics. We envision that this will be similar to the current MINERνAdesign, incorporating an on-board Cockroft-Walton HV supply, eliminating the need for a HV distribution system. Fermilab is currently working on a custom ASIC specifically for silicon photodiodes, and we plan to employ this chip in our front-end boards.

Front-end electronics will be read out by custom interface and timing cards housed in a VME crate. Readout and data acquisition will require a number of dedicated servers. MINERνAemploys a C++ based data acquisition software which could be retooled to work with the upgraded detector. In particular, the readout libraries would have to be re-written in order to communicate with the new electronics.

2.3 Current Design Efforts

The detector description given here is conceptual and requires further studies, optimization, and R&D in order to produce a final design. In its current stage of development, simulations are being used to study the physics capabilities of this detector to determine if it meets the needs of the oscillation program. In general, we are producing efficiencies and purities for the detection of both signal and background reactions in order to understand the detectors performance for comparison to other available detector technologies. As the near detector effort progresses past the conceptual phase, we will further use simulations to refine the design and optimize various detector parameters. Technical issues to be studied in simulation include:

- The amount of target material and its distribution in the detector.
- The thickness of absorber material in the calorimeters.
- The configuration of the magnet for the muon spectrometer.

In order to complete a technical design, several issues will need to be addressed through an R&D effort:

- Selection of the exact photosensor.
- Mechanical design and testing of the photosensor mount to optimize light collection efficiency.
- Initial design and testing of the front end electronics.

R&D plans will be further discussed in Section 4.

3 Infrastructure Needs

Construction and deployment of the LBNE near detectors on the Fermilab site is a large undertaking and will require significant resources, both in terms of personnel and facilities.

3.1 R&D Needs

While the full R&D program will be discussed later (see Section 4), we will mention here that the R&D program call for the development of 1/4 scale sized prototype detector that will eventually serve as our calibration detector. This program will require lab space for on-site assembly of the detector. We plan to run this detector at the Fermilab test beam facility. Following Laboratory policy, we will negotiate a formal MOU with test beam management for access to facilities. For this run, we would like to utilize the tertiary pion beam designed for the MINERνAexperiment.

3.2 Construction Needs

Construction of the downstream hadronic calorimeter will require a large laboratory space with high bay. Construction of MINERνAemployed the entirety of Wideband Hall, and a comparable facility will be required. Our requirements for the facility include:

- Approximately 10,000 square feet of floor space. This will permit welding of required module frames, packaging of the scintillator, and construction and source testing of modules.
- Overhead crane coverage with minimum 10 ton capacity covering both the assembly floor and loading dock.
- A loading dock with large access door.
- Sufficient stands for storage of completed modules.

Existing facilities previously constructed for the MINERνAshould be re-used. These facilities include detector stands, strongbacks, a large automated radioactive source scanner that was used to test detector modules.

In addition to the surface building, the production of the scintillator will require use of the Fermilab extruder facility.

3.3 Installation Needs

The deployment of the near detector will require significant infrastructure on the Fermilab site. If pieces of the MINOS near detector will be re-deployed as a downstream muon catcher for the LBNE near detector, then MINERνAmust be removed from the MINOS near detector hall first and stored at some surface location prior to being redeployed. This not only permits access to the MINOS near

detector, but is required so that the module order is correct in the LBNE near detector hall (The module order reverses every time that the detector is moved.).

From the intermediate facility, modules will be transported to the LBNE surface building, down the shaft and into the near detector hall. Space and facilities are taxed most during detector installation.

While the specific design of the near detector hall and associated surface building will be discussed elsewhere within this CDR, this section will detail needs for the successful deployment and operation of a scintillator tracker near detector.

3.3.1 Intermediate Surface Facility

This intermediate surface facility must meet most of the needs outlined for the construction hall described in Section 3.2, making the construction hall an obvious choice. The LBNE surface building, the near detector hall itself, or some other facility may also be used provided they meet the needs outlined in Section 3.2.

3.4 Surface Building

The surface building provides secure access to the shaft and personnel elevators leading to the near detector hall. The surface building must have a high bay capable of staging material to the shaft crane. For this purpose, we prefer the dual overhead crane arrangement previously employed for the MINOS near detector surface building. One crane can be used to offload material off of trucks and move it around the surface building without the access limitations associated with the shaft crane. The high bay must be a minimum of 30feet high.

As significant amounts of material will be brought down the personnel elevators, we require a minimum aperture of 60" for all access points to the personnel elevator. This includes all doorways, hallways, and access passages.

During the installation phase, a shaft crane operator and technician crew will be required to move modules during periods of installation. It is hoped that these personnel will be available even during periods of accelerator shutdown.

Finally, we will require access to a van for delivery of instrumentation and lighter material to the surface building.

3.5 Near Detector Hall

In order to install the detector, the near detector hall and its access points must be appropriately structured and outfitted. For a MINERνA-like detector, there must be facilities to transport material from the base of the shaft to the near detector hall. At MINOS, this is provided by a cart which is pushed by a battery powered forklift. A similar arrangement would be suitable for LBNE.

Inside the near detector hall, we have a variety of needs:

- A stand suitable for mounting a MINERνA-like detector: The detector must be mounted so that it intersects the nominal path of the beam through the near detector hall.

- A drip ceiling that suitably covers the experimental area: Ground-water will inevitably seep into the experimental hall through the walls and ceiling of the cavern. Some structure must be provided that prohibits this water from falling onto the detector, electronics, and other critical pieces of infrastructure. This must be a structure suspended from the rock which hangs above the level of the overhead crane.

  The MINOS near detector hall was originally constructed with a metal roof that covers the MINOS near detector. As experiments were added upstream of MINOS, the metal roof was not extended. Instead, a coating was added to the cavern surface as a lower-cost alternative.

The vendor claimed that the coating would react with the ground-water in such a way to seal leaks. While the product did slow the seepage of water, it still allows significant persistent leaks which have affected operation of detectors upstream of the MINOS near detector. This kind of coating should be avoided in the LBNE near detector hall.

- Staging area: Open floor space upstream of the detector is required for staging material during installation periods. The minimum floor space required is ??? by ???. The staging area should be covered by the overhead crane.
- Room for supporting materials: In addition to the detector, we require room for electronics racks, a table for use while working on the data acquisition PCs, lockers for storing tools and material.
- Computer networking: Ethernet access is required for the data acquisition computers. In addition, some facility should exist for personnel to access computer networking, such as an active, spare ethernet port.
- Power feeds: Power outlets in convenient locations for the detector and electronics.
- An articulated personnel lift for use during installation periods.

4 R&D Plans

While much of the detector is to be re-used components of the MINERνAdetector, the upgraded muon spectrometer and electronics will require an significant R&D effort. It is currently estimated that R&D funds will be available in the second half of FY2011.

4.1 FY2011-2012

The most pressing need will be selection of photosensors and early design work for the new front-end electronics. This work will be done at Fermilab in conjunction with Paul Rubinov of the Particle Physics Division Electrical Engineering Department. There are several SiPM sensors on the market, and we will test and characterize various models in order to select the most appropriate photosensor for our needs. Once an SiPM has been chosen, Paul will proceed with early design work for the front end electronics, producing a number of prototype boards. We will also begin work on techniques for mounting the SiPMs in order to maximize the light collection efficiency of the detector optics.

As the muon spectrometer will require production of a significant quantity of extruded scintillator, scintillator will be another key early R&D initiative. We plan to research the production of scintillator with a co-extruded wavelength-shifting (WLS) fiber. The MINERνAconstruction technique was for the scintillator to be extruded with a hole running the length of the extrusion. The WLS fiber was inserted into this hole when the scintillator sheets were constructed. Optical epoxy was injected into the voids around the WLS fiber to increase optical contact between the fiber and surrounding scintillator, increasing overall light yields by approximately 30%. As the MINERνAdetector was built, all scintillator was source-tested to characterize the detector optics for calibration purposes. This source testing revealed a large weakness in the MINERνAconstruction technique. In some minority of the channels, the fiber was not completely wetted by the optical epoxy. This imperfect optical coupling produced non-standard attenuation curves for the affected channels. These curves had sudden changes in light levels which were difficult to parameterize for the calibration effort. A typical affected channel is shown in Figure **??**. Insertion of the fiber and injection of the glue was labor intensive, expensive, and produced a non-uniform product.

Anna Pla, who oversees the Fermilab extruder facility, has plans to develop a technique whereby the WLS fiber is inserted into the molten plastic while being forced through the extruder die. If

successful, the resulting scintillator will provide an overall higher light output and more uniform response. We would like to endorse Anna's plan and include it in our early R&D efforts.

Finally, as the scintillator and electronics are produced, we would like to integrate these elements into a small benchtop test setup. A few panels of the new scintillator could be instrumented with the prototype photosensors and electronics. Outfitted with a cosmic-ray trigger, this setup could be used for a number of integration and physics studies (tracking, calibration of the overall muon energy scale for the scintillator).

4.2 2013

In FY2013, we would build parts for a scale model detector. This would be a 1/4 scale size functional detector that would be used to test the upgrades to the standard MINERνAdetector. Conceptually, this detector would would feature an upstream tracking region of several sheets of fine-grained scintillator. The downstream section then would be a small version of the magnetized muon spectrometer.

Components of the detector would be built in FY2013, and it is planned that the component construction would be used to R&D construction of the full-sized detector. Groups producing components for the prototype detector would eventually be responsible for producing components for the near detector. This exercise would provide an opportunity to refine construction techniques, train personnel, and outfit a production site.

Final pieces would be shipped to Fermilab near the end of the summer in 2013.

4.3 2014

In FY2014, we will assemble and commission the prototype detector. The detector will be built on site at Fermilab. The detector components will be 1/4-scale, but will will use actual photosensors and a fairly advanced form of the electronics in order to exercise the full readout chain.

This detector could have a rather versatile run plan. During commissioning, we will initially trigger on comic rays. The detector could be moved to the MINOS near detector hall for some actual neutrino beam running. Finally, it is envisioned that this will also serve as our calibration detector. The detector will be deployed at the Fermilab test beam facility

FY2014 will also be used to finalize any remaining pre-construction R&D, such as production of fixturing for full-sized detector components, revisions to construction protocols based on outcomes from the prototype detector construction, etc.

5 Safety Concerns

The R&D and construction required to produce this detector will involve exposure to a significant number of hazards. Table 5 lists potential hazards we have identified, possible sources of exposure, and specific steps that can be taken for abating the particular hazards.

Detector R&D and construction will occur both at Fermilab and at collaborating institutions, each of which has their own safety policies. To ensure that work is being properly considered by all institutions, we will require all site managers to perform a safety inventory. Site managers will produce a list of possible safety hazards and review this with institutional safety representatives, and any recommendations must be implemented. A list of hazards and institutional remediation will be provided to the project management before any work is performed.

Aside from the construction process, operation of the detector poses additional risks:

1. Underground location: Training will be required for all personnel wishing to access the underground hall for maintenance purposes. Entry will be controlled.

Table 1: Hazards associated with construction of the detector.

Hazard	Possible Exposure	Abatement
Radiation	Radioactive sources will be used in the testing and characterization of various detector components.	Follow institutional guidelines for radioactive materials.
Hazardous Materials	Detector construction could involve significant quantities of epoxy or other potentially harmful materials.	Use care when selecting materials; maintain MSDS sheets. Work with institutional safety to determine needs for PPE.
Working at Heights	Installation will involve work in an articulated personnel lift.	Training in accordance with Fermilab guidelines.
Work with tools	Detector construction will involve hand and possible power tool usage.	Make PPE available (safety glasses); job specific training provided by supervisors.
Work in underground location	Detector will be installed in underground experimental hall	Detector constructed in compliance with Fermilab flammability and toxicity guidelines. Training in accordance with Fermilab guidelines; entry to underground hall will be controlled by procedures similar to those established for the MINOS near detector hall.

2. Strong Magnetic Field: The downstream muon spectrometer will produce a strong magnetic field. The hazard will be posted with specific warning signs, and regions of particularly strong field will be marked. A flashing beacon will signal when the magnet is in operation.

3. High voltage: There will be high voltage in the experimental hall. While the use of Cockroft-Walton HV sources for our front-end electronics minimizes any associated risk, the magnet for the downstream muon spectrometer will require an HV supply. The hazard will be posted, and engineered controls will be placed to minimize risk of personnel exposure to this hazard.