# Chapter 11

# The hybrid emulsion detector

## 11.1 Overview

### 11.1.1 Sensitivity of a low background appearance experiment

The sensitivity of a neutrino oscillation search using the techniques discussed in Chapters 2 and 3 is limited by statistical fluctuations of the background $\nu_\mu$ interactions. Hence it improves with the $\sqrt{\text{mass}}$ (or $\sqrt{\text{running time}}$) of the detector. A background-free appearance experiment which detects the oscillated neutrinos directly has a sensitivity proportional to the detector mass (or running time). For oscillation probabilities on the order of 0.01 its sensitivity approaches that of a thirty times more massive experiment using the NC/CC test.

In addition, a $\nu_\tau$ appearance experiment with explicit detection of $\tau$ leptons is insensitive to the details of the parent neutrino beam (provided that the beam has no $\nu_\tau$ component). Hence it is probably the only way to detect $\nu_\mu \to \nu_\tau$ oscillations if the mixing angle is smaller than $\sim 10^{-2}$.

In this Chapter we describe a hybrid emulsion detector which would complement the physics capabilities of the 5.4 kt MINOS calorimeter. Considerable R&D remains to be done to work out technical details, but we are confident that the experiment is feasible and could be an early addition to the baseline MINOS detector.

### 11.1.2 Progress in emulsion and automatic analysis techniques

Nuclear emulsions have a long history of use in high energy physics. Their unsurpassed spatial granularity and resolution make them particularly suitable for the detection of very short lived particles. In recent years nuclear emulsions have been used in a number of neutrino experiments as a tool for detecting $\tau$ leptons, including CHORUS[1] at CERN and E-872[2] at Fermilab. In addition, nuclear emulsions remain an important technique for studies of the highest energy cosmic ray interactions, for example in the JACEE Collaboration[3].

The nuclear emulsions used today are very similar to those used fifty years ago[4]. The analysis techniques, however, have changed dramatically: electronic detectors are used to localize events and advances in microcomputers have been exploited to increase scanning speed. The Nagoya University group has constructed several stations consisting of computer controlled microscopes read out with CCD cameras and equipped with automatic hardware track recognition and reconstruction processors[5]. These stations are being used to analyze hundreds of thousands of events from the CHORUS experiment.

These capabilities for large scale automatic analysis of emulsion data are changing the way that emulsion sheets are used in experiments. The ECC approach[6], in which thin emulsion sheets interspersed with passive material serve as a target, is becoming widely used in cosmic ray studies. The nuclear emulsion sheets are used as very fine granularity, high spatial resolution tracking detectors with the particles of interest traversing the sheets perpendicular to the surface. Such a configuration has been employed recently in an experiment designed to directly observe $\nu_\tau$'s, E-872 at Fermilab[2].

### 11.1.3 The principle of the emulsion experiment

If $\nu_\mu \to \nu_\tau$ oscillations take place, $\tau$ leptons will be produced via the charged current interaction. These leptons will decay with a typical path length of a few hundred microns. In three pronged decays (14.4%) there will be three charged particles leaving the decay point. One pronged decays (85.5%) are characterized by a substantial "kink" on the original trajectory, with a typical kink angle of the order of a hundred milliradians.

The experiment will consist of three components:

- Target planes. These will be thin plates of a dense material where the neutrino interactions take place. The number of registered interactions is proportional to the total mass of the target planes, whereas the number of $\tau$ leptons leaving the target, and hence detectable, is inversely proportional to the thickness of a target plane. Thus a high density target material is optimal. Lead is a natural candidate.
- Tracking planes ($\tau$ detecting planes). The tracking planes follow the target planes. They must provide enough tracking information to identify three body decays and/or to identify the decay kink. The short lifetime of the $\tau$ lepton requires these measurements to be made in the space of $\sim$1 mm. There are several possible geometries of the emulsion sheets which can accomplish this task. The most conservative uses two 2-sided emulsion sheets at the entry and exit of the tracking volume (see Figure 11.1). The first emulsion sheet will measure the direction of the incoming $\tau$, the second will measure the direction of the outgoing daughter from the $\tau$ decay. The emulsion sheets are composed of a 100 $\mu$m thick plastic base and 100 $\mu$m thick emulsion layers on both sides of the base. A 400 $\mu$m thick plastic layer separates the emulsion sheets and provides the decay volume.
- Triggering/event localization planes. These planes, spaced with a frequency of about a quarter of an interaction length throughout the entire detector, will be electronic detectors, used to identify where neutrino interactions took place and reduce emulsion scanning effort.

### 11.1.4 A modular, extensible design

We plan to construct the detector from a large number of small "modules," each of which is an independent subassembly of target and emulsion planes. A module is built as a mechanically

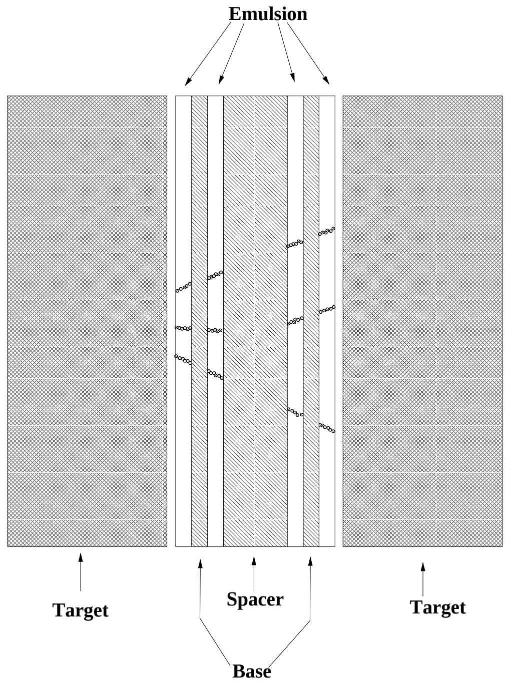



Figure 11.1: Target and tracking plane geometry of the hybrid emulsion detector. Two double-sided emulsion sheets measure the angles of particles at the entrance and exit planes of the tracking volume.

separate box which contains ~50 planes of emulsion and target material. Each module is approximately 10 cm thick and 15 $\times$ 15 cm$^2$ in transverse dimensions. Large planes of modules (~1000 for a 5 $\times$ 5 m$^2$ detector) are interspersed with triggering planes. Module planes are constructed so that individual modules can be extracted and replaced by fresh ones as interesting events are identified by the triggering planes. This might be done on a weekly basis, thus permitting near-on-line analysis of the emulsion data. The triggering planes also localize charged particles with an accuracy of the order of 1 mm, which greatly reduces the scanning effort.

The modular design allows an adiabatic extension of the size and potential of the experiment. New modules can be added to the detector, thus extending the sensitivity to neutrino oscillations, without disruption of the data taking. It offers significant flexibility and enables a physics- or fiscally-driven optimization of the experimental strategy.

If $\nu_\mu \to \nu_\tau$ oscillations occur with a large mixing angle, and $\Delta m^2$ is in the upper part of the range suggested by Super-Kamiokande's atmospheric neutrino results, then a modest size detector of ~100 tons is sufficient to observe an unambiguous signal.

If the oscillations are suppressed due to the low value of $\sin^2(2\theta)$ ($< 0.01$) or $\Delta m^2$ ($< 0.001$ eV$^2$), then future extension of the emulsion detector to a total mass of 1000 tons, exposed for several years, is probably the only practical technique to detect these oscillations.

## 11.2 Physics potential

### 11.2.1 Event rates

We assume the high-energy neutrino beam configuration with a $\nu_\mu$ CC interaction rate of 3000 ev/kt/year and an average neutrino energy $\langle E_{\nu_\mu} \rangle = 17.6$ GeV. The rate of $\nu_\tau$ interactions is reduced by kinematic effects depending on $\Delta m^2$. We assume here $\sigma^{CC}_{\nu_\tau} / \sigma^{CC}_{\nu_\mu} \approx 1/3$.

### 11.2.2 Tau neutrino detection efficiency

The detection of a $\tau$ lepton requires the identification of a decay kink in the space between target plates, or of a track which does not come from a common neutrino production vertex. If the event has more than one track at the production vertex, an extra track with a finite impact parameter relative to the reconstructed vertex is required. Otherwise two non-intersecting tracks signal a $\tau$ decay. The combined detection efficiency $\varepsilon$, estimated with a detailed GEANT simulation, is of the order of 50%.

### 11.2.3 Background rejection

The chief background for $\tau$ detection will probably come from D meson production and subsequent decay in $\nu_\mu$ CC interactions. In addition to the suppression of the charm cross section, due to the low energy of the beam, the main rejection factor will come from detection of the accompanying muon in the large MINOS spectrometer following the emulsion detector. It is important to notice that this background rejection technique does not imply that the $\tau \to \mu$ decay mode cannot be used to detect $\tau$'s. In the case of $\tau$ decay the decay kink occurs on the muon track, in contrast to the charm decay topology.

Associated production of charm particles, both in CC and NC interactions is further suppressed by kinematical factors to a level well below the single charm production.

The decay or interaction of $\pi$ and K mesons produced in NC $\nu_\mu$ interactions are yet another potential source of background but they are expected to be negligible in the very short distances in which $\tau$'s decay.

The detailed evaluation of background requires the detector geometry and composition to be defined in a full GEANT simulation and the analysis procedures to be established, hence it is not yet possible. Based on the initial estimates and on the experience of other emulsion experiments, we do not expect the total background rate to exceed a small fraction of one event per kt-year.

An important feature of this experiment is the ability to measure actual background levels in a small emulsion detector installed in the MINOS near hall, where we expect the flux of $\nu_\tau$'s to be very low. Because of the high $\nu_\mu$ rate in the near hall, this detector can be small, and will allow any unexpected background to be identified very early in the experiment.

### 11.2.4 Electron identification capability

The strength of nuclear emulsion is its high granularity and spatial resolution, making it the only detecting technique capable of unambiguous event by event $\tau$ identification. It should also be noted that nuclear emulsions provide a very good tool for the identification of primary electrons.

Electron candidates can be recognized by the presence of converted photons from the electromagnetic cascade along the initial charged particle trajectory. Emulsions provide a very good rejection power against photons from $\pi^0$ decays. Most photons will convert at an observable distance from the primary vertex. The majority of photons which convert in the immediate vicinity of the interaction vertex, and electrons from Dalitz decays of $\pi^0$'s, can be rejected by the presence of two charged tracks, taking advantage of the spatial granularity of nuclear emulsions.

With these very good background rejection capabilities, the potential for discovery of $\nu_\mu \to \nu_e$ oscillations will be limited only by the statistical fluctuations of the intrinsic $\nu_e$ component of the beam and the systematic error on the extrapolation of this component from the near to far detector locations.

### 11.2.5 Oscillation discovery potential

We assume a 1 kt-year exposure for illustration.

The number of observed $\nu_\tau$ interactions will be

$$N_\tau = P \times N_{\nu_\mu} \times \frac{\sigma_{\nu_\tau}}{\sigma_{\nu_\mu}} \times \varepsilon,$$

where P is the average oscillation probability. For large $\Delta m^2$, $P = \frac{1}{2}\sin^2(2\theta)$.

If no $\nu_\tau$ events are observed, the experiment will set a 90% CL limit at

$$\sin^2(2\theta) < \frac{2 \times 2.3}{4000 \times 0.33 \times 0.5} = 7 \times 10^{-3}.$$

The limit improves with the running time like $t$, assuming no background.

The lowest $\Delta m^2$ detectable in the experiment is related to P via

$$\Delta m^2 = \frac{\sqrt{P} \times \langle E_\nu \rangle}{1.27 \times L},$$

and for the above conditions is $\Delta m^2 \geq 1.6 \times 10^{-3} eV^2$ . This limit improves with running time like $\sqrt{t}$.

## 11.3 Module construction

### 11.3.1 Target planes

The target planes serve as a source of $\tau$'s. They should be as massive as possible to maximize the interaction rate, and as thin as possible to maximize the number of $\tau$'s escaping. Practical considerations favor lead as a target material.

The determination of the optimum thickness of the target plates requires an optimization of the overall number of detected $\tau$'s *vs* size and cost of the detector. Our present design is based on 1 mm thick lead sheets cut to 15 cm $\times$ 15 cm size.

Prolonged contact with most metals, including lead, leads to severe fogging or even decomposition of nuclear emulsions. The emulsions will be insulated by a protective layer of acrylic paint on the lead surface, following the technique developed by JACEE[7].

### 11.3.2 Emulsion tracker

Typical nuclear emulsion yields some 40 developed grains per 100 $\mu$m of a minimum ionizing track, thus offering a considerable potential for particle identification via dE/dx. In this experiment we will use emulsions only for position and direction measurements, therefore our requirements on the grain density will be dictated by pattern recognition considerations. It is expected that emulsions produced and exposed in the mine will provide a very clean environment[8], therefore of the order of 20 grains per 100 $\mu$m should be sufficient for high efficiency track detection.

Studies of diluted emulsions[9] show that the desired grain density can be achieved with a significantly lower concentration of silver halide in the gel, thus offering the potential for a substantial reduction in the cost of the nuclear emulsions. We envisage using the emulsions diluted by a factor of four with respect to the standard composition. Such a dilution has an additional advantage: the shrinkage of the emulsion during the fixing process is reduced from a factor 2.4 to 1.34. This, in turn, leads to a substantial reduction of distortions in the emulsion, making the angular measurement less prone to systematic errors.

The 100 $\mu$m layers of emulsion will be poured (in turn) on both sides of a 100 $\mu$m thick polystyrene base. After the drying process the emulsions sheets will be imprinted with fiducial marks and cut to 15 cm $\times$ 15 cm.

### 11.3.3 Packaging

Modules will be packed into thin stainless steel cans 15 cm $\times$ 15 cm $\times$10 cm, resembling those used in the canned food industry.

Packaging of the target plates and emulsion sheets into modules will be carried out in a darkroom. Lead plates, emulsion sheets and the spacer plastic sheets will be loaded into the steel can. The can will subsequently be evacuated and hermetically sealed. It is expected that the pressure loading of the plates will ensure that the relative positions of the emulsion sheets will not change with time.

## 11.4 Trigger and event localization detectors

The trigger plane detectors will be used to record neutrino interactions and identify the tracking modules traversed. These modules will be subsequently removed from the detector for the analysis of the nuclear emulsions. Position and directional information from the trigger planes will be used to direct the track search in the emulsion sheets and to reduce the analysis load. For this purpose a position measurement accuracy of a few mm is adequate.

### 11.4.1 Iarocci tubes

Iarocci tubes have been extensively used in high energy physics experiments[10]. They are an attractive solution when a robust and inexpensive tracking detector is needed, and can be used either in drift mode or with cathode strip readout. Recently Iarocci tubes have been proposed as the forward muon tracking detectors for the D0 upgrade project[11]. We have considered Iarocci tubes as a possible active detector for MINOS and have acquired a substantial amount of experience with these detectors.

Several experiments have demonstrated that Iarocci tubes can be reliably operated in large scale systems, with detection efficiency in the active areas close to 100%. Geometrical effects, mostly due to the walls of the chambers, reduce the efficiency to a typical level of 95%, dependent somewhat on the angular spectrum of incoming particles.

### 11.4.2 System layout

The Iarocci tubes will be organized into tracking planes, 5 m $\times$ 5 m in size. Each plane will be built out of 8-cell modules, 8.34 cm wide and 5 m long. Two-dimensional position information will be derived from the wires and from signals induced on the cathode strips running across the modules. Both sides of the tracking plane will be covered with thin aluminum sheets, serving as a Faraday cage. A complete plane will have 480 wires and 500 strips. It will have an overall thickness of 1.5 cm.

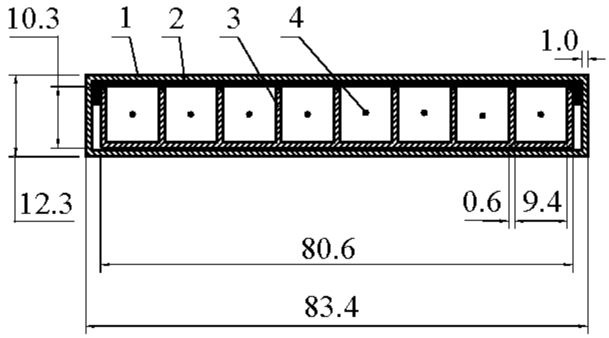
D0 is planning to use Iarocci tubes in drift mode with a fast gas mixture (90% $CF_4$ + 10% $CH_4$) to keep the maximum electron drift time below 60 ns and give a position resolution of $\sim$1 mm. For our application the requirements on speed, rates and radiation damage are relaxed significantly; our most important requirements are those of safety and reliability. We expect to replace the D0 gas mixture with some more standard and less expensive mixture. We plan to use the tubes in counter mode and expect a resolution of about 3 mm from anode wire information. Position determination using cathode strips will be significantly better, depending on strip width. In the test beam studies of MINOS prototypes a resolution about 1 mm was obtained with 1 cm strips. Typically Iarocci tubes with 1 cm cathode strips have resolutions of $\sim$0.5 mm[12].

### 11.4.3 Design of an 8 cell module

These modules will be built in a manner similar to the D0 muon chambers, with the equal length of modules offering a significant simplification.

An individual module will have 8 cells with 9.4 mm $\times$ 9.4 mm internal cross section and with a 50 $\mu$m W-Au anode wire in the center, as shown in Figure 11.2. The tubes will be made from commercially produced aluminum extrusions with a wall thickness of 0.6 mm. They will be inserted into 5 m long PVC plastic sleeves.

The tubes will be closed by endcaps which will provide accurate positioning of the anode wires together with electrical and gas connections. The mechanical tolerance of the wire position within the tubes, ensured by automated assembly procedures, is 160 $\mu$m, well below the intrinsic coordinate resolution of the detector. The bottom endcaps will have gas connectors, HV connectors and individual signal connectors for 8 wires. The top endcap will




1 – envelope
2 – cover
3 – profile
4 – wires

Figure 11.2: End view of an 8-cell module of Iarocci tubes. The dimensions shown are in mm. The "cover" is not needed for our application.

have gas connectors only. The modules will be glued on the surface of the external cathode strip boards. The U.S. CMS muon system project has constructed a facility for strip board production at Fermilab. It produces boards with a dimensional tolerance on strip locations of about 50 $\mu$m, which is more than adequate for our purposes.

As a part of D0 muon upgrade project, the front-end electronics (8-channel amplifiers and discriminator chips) have been developed by the Dubna group and the Integral company in Minsk, Belorussia. These amplifiers are adequate for our purposes.

## 11.5 Detector construction

### 11.5.1 Honeycomb construction

We plan to construct 5 m $\times$ 5 m $\times$ 10 cm target and emulsion planes in a honeycomb box geometry, as shown in Figure 11.3. Each box will be constructed from 1 mm thick front and back steel plates interconnected every 15.5 cm with horizontal steel strips, forming a set of 10 cm wide, 15.5 cm tall and 5 m long channels. A series of 2.5 m long trays loaded with the emulsion modules will be inserted into these channels from both sides of the detector.

At regular time intervals during the experiment, some of the trays will be slid out of the detector, the modules indicated by the tracking planes will be removed and replaced by new modules, and the whole assembly will be placed back into the detector.

An individual module will weigh some 13 kg, thus allowing easy manipulation. The entire tray of modules will weigh 250 kg. The removal and replacement of the modules will therefore require the construction of a movable support structure with appropriate lifting capabilities.

A single plane with modules will have a mass of about 15 tons. It is expected that its

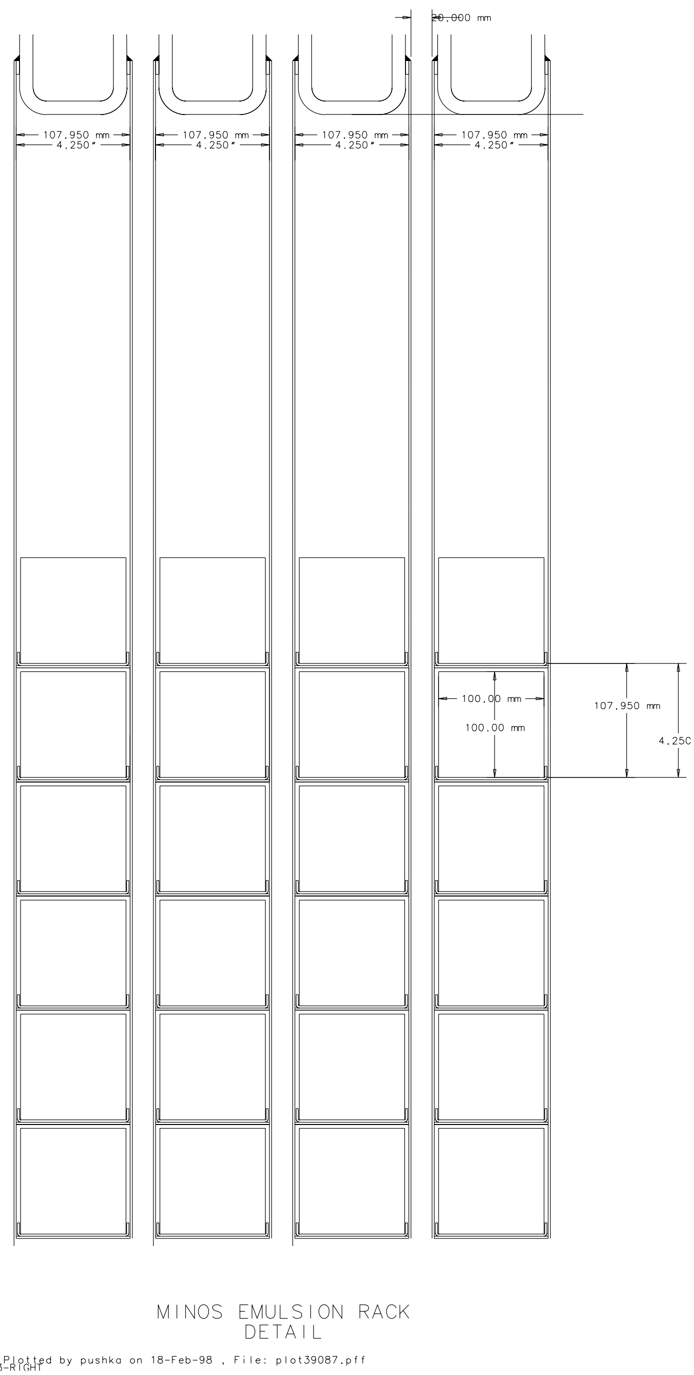



Figure 11.3: Side view of the honeycomb box structure containing the target and emulsion modules. The modules are shown as 100-mm wide × 100-mm tall boxes. (Note that 100-mm wide × 155-mm tall modules are described in the text.) The four planes shown are suspended from the structural beams at the top. The triggering planes, which would be located between the planes of emulsion modules, are not shown.

load will be transferred by the front and back steel plates to a structural member on top of the plane, which in turn will be hanging off the support rails on both sides of the detector, as shown in Figure 11.4.

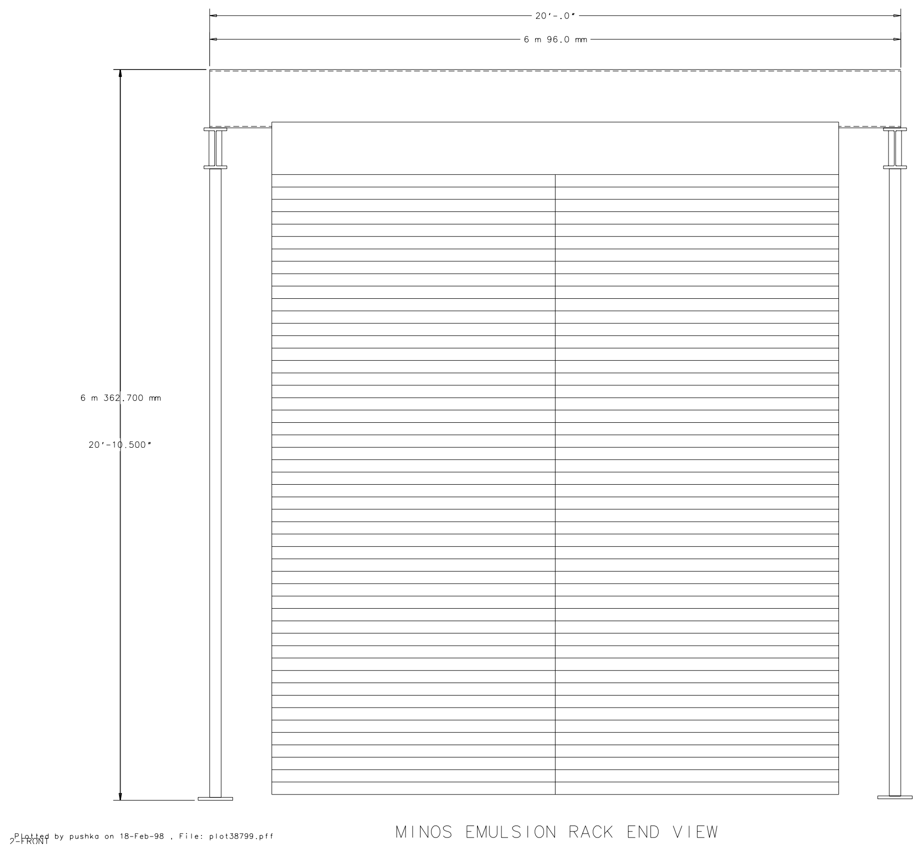



Figure 11.4: End view of an emulsion detector plane, as seen by the neutrino beam. The 5 m $\times$ 5 m detector planes are suspended from the structural beams at the top, which are supported by rails on the two sides of the detector.

### 11.5.2 Detector support structure

The detector will consist of an alternating series of target/emulsion planes and triggering/event localization planes. Both kinds of planes will hang from the structural member on top of each plane. These structural members will be supported by two rails on both sides of the detector (hanging file design) as shown in Figure 11.4 .

The target/emulsion planes will be separated by 2 cm from the triggering planes. This leads to an average density of the detector of 125 tons/meter.

### 11.5.3 Space requirements

Muon identification requires that the detector be placed in front of the 5.4 kt MINOS detector. The MINOS baseline design includes a 10-m long section of the underground cavern, upstream of the 5.4 kt detector, for future upgrades such as the emulsion experiment. As discussed above we expect the emulsion detector to start with a limited mass, of the order of 100 tons, and grow with time subject to physics and fiscal considerations. We envisage that the total mass of this detector can reach up to 1 kt. The emulsion detector would be constructed in the upstream direction, starting from the modules immediately in front of the MINOS toroids.

### 11.5.4 Module assembly factory

We consider it desirable that the entire construction of the emulsion detector, including manufacturing of the emulsion sheets, should be conducted in the Soudan mine to reduce cosmic ray background in the emulsions.

Module production in the mine will necessitate construction of several underground facilities for pouring and drying the emulsions and for construction of the target/emulsion modules. These facilities must be equipped with darkroom lighting conditions and with adequate environmental control, humidity being the most critical factor.

We expect that these facilities will be constructed in the area in front of the MINOS toroids or in the Soudan 2 cavern. Neither the space requirements nor safety considerations are expected to make construction of these facilities difficult.

### 11.5.5 Near detector

The sensitivity of the hybrid emulsion experiment relies on its ability to detect $\tau$'s with no background. The lack of background will be demonstrated by measurement in an environment where it is known that the flux of $\nu_\tau$ is very small, i.e., at the near detector. We propose to measure background levels with a small detector in the form of a $4 \times 4 \times 6$ array of modules (60 cm $\times$ 60 cm $\times$ 60 cm deep). This would cover the central portion of the beam which, in the absence of oscillations, has a neutrino energy spectrum very similar to that at Soudan.

## 11.6 Research and development program

There is little doubt that the hybrid emulsion experiment described above can be constructed, and that it would be capable of highly efficient detection of $\tau$'s while maintaining background-free conditions at our desired sensitivities. Its construction is well within our present technical capabilities. The data analysis load, other than emulsion processing, is expected to be minimal.

The main obstacle is financial. The cost of construction of a 1 kt detector with present technology would be of the order of $100M, well outside practical bounds, although a 100 ton detector could be feasible. We plan to conduct a vigorous program of R&D to optimize the detector design and its construction techniques to reduce the cost by an order of magnitude.

This program is focused on the likely cost drivers: the nuclear emulsion and the module construction.

### 11.6.1 Nuclear emulsion optimization

Nuclear emulsions are a very mature technology. Modern emulsions offer high sensitivity, yielding some 40 grains of developed silver per 100 $\mu$m of minimum ionizing track, while maintaining very low random grain backgrounds at the level of 3 grains per 10 $\mu$m $\times$ 10 $\mu$m $\times$ 10 $\mu$m volume[13].

In the proposed experiment a thin sheet of nuclear emulsions will be used as a high resolution tracking detector. The grain density requirements will be dictated by the detection efficiency and pattern recognition considerations. The former will be satisfied by having 20 or more grains per 100$\mu$, the latter depend very much on the environment in the emulsion.

The current generation of neutrino experiments is carried out in a high background environment, far exceeding cosmic ray backgrounds. This will not be the case in the Soudan mine. We expect the environment there to be very quiet for emulsions[8]. Although we need to evaluate the environment at Soudan, we expect that emulsion with a grain density of the order of 20 will be sufficient for our purpose. In this case, considerable savings can be achieved by diluting the standard emulsion with gelatin. Studies have shown that a four-fold dilution of emulsion leads to less than a factor of two reduction of the grain density on the charged particle trajectory, see Table 11.1[9]. This somewhat surprising result is probably due to the increase of the sulphur density around the silver halide grain in the diluted emulsion.

| Designation | $\frac{\text{Halide vol.}}{\text{Total vol.}}$ | Shrinkage factor | Density g/cm$^3$ | $n_{min}$ (100 $\mu$m)$^{-1}$ |
|---|---|---|---|---|
| "Normal" (G.5) | 0.49 | 2.30 | 3.9 | 36 |
| 2 $\times$ normal | 0.35 | 1.67 | 3.2 | 33 |
| 4 $\times$ normal | 0.23 | 1.34 | 2.5 | 21 |
| 8 $\times$ normal | 0.13 | 1.17 | 2.0 | 10 |

Table 11.1: Properties of nuclear emulsion as a function of dilution with gelatin.

We plan to repeat these studies with the currently produced emulsions. In particular we plan to construct emulsion stacks using diluted emulsions and to evaluate the track finding efficiency as a function of the dilution factor.

### 11.6.2 Evaluation of the Soudan environment

Pattern recognition efficiency and potential error rates are strongly related to the background environment. In our case the background will be a combination of randomly developed grains, cosmic ray muons, muon-induced electrons and Compton electrons due to the ambient radioactivity. The cosmic ray-related component will be strongly dependent on the emulsion production and processing conditions. One day on the surface is equivalent to several years underground.

We plan to conduct a systematic study of the backgrounds for emulsions produced on the surface and in the Soudan mine. The results of these studies will provide a quantitative input to the emulsion optimization discussed above and will determine whether the production of emulsions and of the target/emulsion modules should be conducted underground.

Taking advantage of the low background environment, the Soudan mine is currently used to store emulsions for the E-872 experiment and in the past has been used for emulsion storage for other experiments

### 11.6.3 Optimization of the emulsion sheets geometry

The function of the emulsion tracker is to determine the angles of the tracks entering and leaving the space between the target plates. We have adopted a conservative design using two pairs of double sided emulsions to measure the track angles at both sides of the gap. This technique is relatively insensitive to systematic problems related to distortions of the nuclear emulsions during the processing, as the grains in the vicinity of the base plate remain stationary and thus provide reliable direction information. At the same time they can be used to self-calibrate the distortions of the emulsion sheets, provided there are enough tracks in the region of interest.

Distortions in the emulsions are, in large part, due to the fact that almost half of the emulsion volume is removed during the fixing stage and the collapse of the resulting voids leads to displacement of gelatin molecules. This effect will be greatly reduced in the diluted emulsions, as the total reduction of the volume is much smaller. It is therefore possible that the angle measurement in a single 100 $\mu$m thick layer will be accurate enough for our purposes. Should this be the case, a simpler geometry with 800 $\mu$m plastic base and double-sided 100 $\mu$m emulsion would be much more economical and easier to manufacture and to analyze.

We plan to construct several stacks of emulsion sheets and evaluate their measurement capabilities in these two geometries. Stacks will be exposed to an 8 GeV Fermilab booster beam which will provide a flux of particles with well known directions.

### 11.6.4 Construction techniques

The geometrical layout of the proposed experiment is very similar to that used in present experiments, E-872 and JACEE, hence the intrinsic feasibility of the construction is not in question. The biggest challenge comes from the scale. We are planning to construct a detector up to three orders of magnitude bigger in total target mass than anything currently existing (the anticipated amount of emulsion required is only a factor of 30 greater, however). Although the present pouring and construction techniques are in principle applicable, we believe that a significant increase in the quality of the large scale detector and a reduction of manufacturing cost can be achieved by employing automated production techniques. This need for automation arises from an expected shift in the relative costs of different components. With the expected reduction of cost of the nuclear emulsion, due to dilution of the silver halides, the construction cost will become a much bigger fraction of the overall costs than in the past.

We plan to experiment with more automated processes to produce emulsion sheets, perhaps with some of the processes used in the photographic film industry.

We also plan to experiment with various methods of automated packaging: stacking, vacuum wrapping, canning etc.

### 11.6.5 Measurement of backgrounds

We expect that the background to the $\tau$ sample will be small and will come predominantly from charm particles produced in the $\nu_\mu$ interactions. Detailed simulations indicate that the background due to scattering and/or interaction of pions produced in NC $\nu$ interactions in the plastic layer separating the emulsions will not produce any significant background. We plan to measure this background component by exposing prototypes of our target/emulsion modules to a low energy hadron beam before neutrino running begins. The total number of pions produced by neutrino interactions in a one year exposure at Soudan is of the order of few thousand. Therefore it will be very simple to determine the background level to below 0.01 event in a short experiment. At the same time, such an exposure will be of great value as a test of the detector construction, performance and analysis techniques. Our calculations of background levels can be convincingly verified by the exposure of an emulsion near detector, as described above.

# Chapter 11 References


[1] M. de Jong *et al.*, (CHORUS) "A new search for $\nu_\mu \to \nu_\tau$ oscillations," CERN-PPE/93-131.

[2] B. Lundberg *et al.*, 1994, Fermilab Proposal P-872.

[3] T.H. Burnett *et al.*, "JACEE Emulsion Chambers for Studying the Energy Spectra of High Energy Cosmic Ray Protons and Helium," Nucl. Instr. Meth. **A251**, 583, (1986).

[4] C.F Powell, P.H. Fowler and D.H. Perkins, "The study of elementary particles by the photographic method," Pergamon Press (1959), W.H. Barkas, "Nuclear research emulsions," Academic Press (1963).

[5] T. Nakano, Ph.D. Thesis, University of Nagoya (1998).

[6] O. Minakawa *et al.*, "Emulsion Chamber Project," Institute for Nuclear Study, Univ. Tokyo Report, INSJ-7, Tokyo (1958).

[7] R.J. Wilkes, private communication.

[8] J.J. Lord, private communication. He has poured, exposed and processed nuclear emulsions in Homestake mine.

[9] Dodd and Waller in J.W. Mitchell (Editor), "Fundamental mechanisms of photographic sensitivity," proceedings of a symposium held at the University of Bristol, March 1950, London, Bitterworth's Scientific Publications, 1951, p.266. Also quoted in M. Shapiro, "Nuclear Emulsions," and in S. Flugge (Editor), "Encyclopedia of Physics," Vol XLV, Springer-Verlag, Berlin (1958).

[10] W. Busza *et al.*, "Experience with Iarocci tubes produced on a large scale," Nucl. Instr. Meth. **A265**, 210 (1988); G. Alexeev *et al.*, "Studies of stability and systematics of operation of DELPHI plastic tubes," Nucl. Instr. Meth. **A292**, 551 (1990).

[11] G. Alexeev *et al.*, "Technical Design Report for the D0 forward muon tracking detectors based on mini-drift tubes," D0 Note 3366 (1997).

[12] N. Khovansky *et al.*, "Spatial resolution of profile-based detectors with external pick-up strips," Nucl. Instr. Meth. **A351**, 317 (1994).

[13] K. Niwa, Nagoya University, private communication. This figure applies to typical Fuji emulsions.