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NuMI-L-473

The Hybrid Emulsion Detector for MINOS

R&D Proposal

Version 3.0

April 1999

The MINOS Collaboration

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The MINOS Collaboration

Main Injector Neutrino Oscillation Search

April 1999

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Executive summary

The MINOS (Main Injector Neutrino Oscillation Search) experiment is designed to search for neutrino oscillations with a sensitivity significantly greater than has been achieved to date. The phenomenon of neutrino oscillations, whose existence has not been proven convincingly so far, allows neutrinos of one "flavor" (type) to slowly transform themselves into another flavor, and then back again to the original flavor, as they propagate through space or matter.

The MINOS experiment is optimized to explore the region of neutrino oscillation "parameter space" (values of the Δm^2 and $\sin^2 2\theta$ parameters) suggested by previous investigations of atmospheric neutrinos: the Kamiokande, IMB, Super-Kamiokande and Soudan 2 experiments. The study of oscillations in this region with a neutrino beam from the Main Injector requires measurements of the beam after a very long flight path. This in turn requires an intense neutrino beam and a massive detector in order to have an adequate event rate at a great distance from the source.

We propose to enhance significantly the physics capabilities of the MINOS experiment by the addition of a Hybrid Emulsion Detector at Soudan, capable of unambigous identification of the neutrino flavor. Recent developments in emulsion experiments make such a detector possible, although significant technological challenges must be overcome. We propose to initiate an R&D effort to identify major potential problems and to develop practical solutions to them.

In addition to this primary motivation for this R&D work, we note that the strong and growing interest in studies of neutrino oscillations using neutrino beams from future muon storage rings provides another potential application. These beams will offer significantly higher intensities, albeit of mixed ν_μ and ν_e, beams. In order to take full advantage of these beams for neutrino oscillation studies it will be necessary that the detector be capable of determination of the flavor of the final state lepton, and the lepton's charge in a significant fraction of the interactions. At present, an emulsion detector in an external magnetic field appears best suited to offer such capabilities. The R&D effort discussed here will be an important step towards a design of such a future detector.

This document is organized as follows:

- Chapter 1 summarizes the physics motivation for the proposed emulsion detector,
- Chapter 2 briefly reviews the status of the emulsion technology and its aplication to particle physics experiments,
- Chapter 3 discusses design considerations for an emulsion detector,
- Chapter 4 describes some of the details of a possible detector as well as results from the work up to date,
- Chapter 5 outlines the proposed R&D program and summarizes the resources required.

This proposal is meant to be a summary of the work we feel is needed before a credible conceptual design report can be produced. It summarizes both the tasks that need to be done and new incremental resources that are required to perform them. It is our expectation that various individual institutions (those currently in MINOS and others anticipating joining) will submit separate individual funding requests, to funding agencies in both US and abroad, to provide most of the resources listed in Chapter 5. We intend that the present proposal should serve as a supplementary umbrella document, outlining the scope of the whole program.

Our primary purpose in submitting this proposal is to obtain Fermilab endorsement of our goal to produce a hybrid emulsion detector conceptual design report on a time scale which is competitive with similar efforts overseas. Failure to demonstrate a credible plan to have an initial emulsion detector in place when the NuMI beam turns on may effectively concede this field to the Europeans. We understand that Fermilab can provide only a small fraction of the R&D funds required during FY99 and FY00. However, only a modest level of support is needed to establish a core program at Fermilab, which would legitimize the funding requests of collaborating institutions to their funding agencies, both in the US and overseas. Fermilab endorsement of this R&D program will also provide the necessary organizational structure for the work, and will help to encourage new collaborators to join our effort. We believe that a core group of two or three Fermilab physicists, support for two or three guest scientist positions, and $250K for M&S will be sufficient to accomplish this.

We expect that, given the required resources, we should be able to establish a credible design of a realistic detector by the end of FY'00. We further expect that a relatively small detector, with a total mass of the order of 100 t, can be constructed in time for the start of the NuMI neutrino beam, by the end of FY'02. This detector could be gradually expanded to a final size of 1kt by the year FY'04.

Chapter 1

Physics Motivation

1.1 Status of Neutrino Oscillations

Neutrinos are known to be among the fundamental building blocks of our universe. Even though we have learned a lot about them since their first observation by Cowan and Reines in 1956[1], they are still poorly understood today. Among the key unresolved questions are whether neutrinos have mass and whether they mix, i.e. can have allowed transitions from one flavor to another.

The minimal version of the Standard Model has massless, and hence non-mixing, neutrinos. Vanishing mass of neutrinos in the Standard Model is an *ad hoc* assumption in contrast to photons, whose zero mass is a consequence of the local gauge invariance. Most of the extensions of the Standard Model predict neutrino masses, of Dirac or Majorana types, and the possibility of mixing.

The possibility of neutrino mixing was first postulated by Pontecorvo[2]. Since that time a variety of experimental efforts have searched for evidence of neutrino oscillations. Except for one result from a Los Alamos experiment[3], all of the searches so far utilizing laboratory-produced neutrinos (i.e., from accelerators, reactors or radioactive sources) have given null results. There is now, however, strong evidence for neutrino oscillations from naturally-occurring neutrinos.

The earliest hints of neutrino oscillations came from the studies of solar neutrinos. The pioneering experiment of Davis[4], using a chlorine detector in the Homestake mine, showed a deficiency of detected neutrinos. A possible explanation of this result could be oscillations of solar ν_e's into other neutrino flavors, which would appear inert in this detector. Since that time, other experiments have confirmed the solar neutrino deficiency and provided evidence for energy dependence of this depletion[5]. On the theoretical side, the work of Mikheyev, Smirnov, and Wolfenstein[6], has provided a possible elegant way of explaining all of the solar neutrino data through the mechanism of matter enhanced oscillations (MSW effect). Thus we can say that the solar neutrino data provide today strong hints for the existence of neutrino oscillations.

The study of atmospheric neutrinos, initiated more than a decade ago, provides today the strongest evidence for neutrino oscillations. Furthermore, the most likely oscillation parameters are such that they are amenable to rigid tests in controlled terrestrial experiments.

The initial evidence, from the Kamiokande[8], IMB[7] and later Soudan2[9] detectors indicated a deficiency in the observed ν_μ/ν_e ratio as compared to the expections from cosmic ray flux calculations. More recently, much stronger evidence was presented by the Super-Kamiokande Collaboration[10], who showed that the ν_μ's suffer depletion with respect to theoretical prediction, which has zenith angle (and hence flight path) dependence. The original Kamiokande data gave first hints of the existence of such an effect[11]. The observed depletion fits very well the hypothesis of $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2 (Fig. 1.1).

The observed anomalies in the upward going muon flux (from Kamiokande[12], Super-Kamiokande[13], and MACRO[14] experiments) both in rate and in zenith angle dependence are consistent with such an explanation.

The atmospheric ν data suggest a different set of oscillation parameters than the solar ν observations. Hence, if both sets of experiments have detected neutrino oscillations, the oscillations must be due to transitions between different neutrino mass states. The previously mentioned Los Alamos experiment does not fit easily into any explanation of solar or atmospheric ν oscillations. Thus if those results are also due to oscillations, the whole picture is considerably more complicated than one might expect from the simplest models.

1.2 The MINOS Experiment and its Goals

The MINOS experiment[15] has been designed to explore a large region in the oscillation parameter space for ν_μ's. The area of exploration spans the Super-K suggested range of parameters and the main focus of the experiment is a detailed study of this region. The experiment will use a newly constructed neutrino beam at Fermilab[16] with the neutrinos being produced by the extracted 120 GeV proton beam from the newly constructed Main Injector synchrotron. The neutrino beam will be composed primarily of ν_μ's (with about 0.6% ν_e component). The beam can span an energy range $1 \leq E_\nu \leq 25$ GeV, depending on the tune and location of the focusing elements.

The principal MINOS detector will be a 5.4 kt iron/scintillator spectrometer, currently in its final design phase (Fig. 1.2). The interactions will take place primarily in 2.54 cm thick iron plates, octagonal in shape, and 8m in diameter. Interleaved between iron plates will be active detector elements: 4cm wide scintillator strips which will yield position and energy information. A toroidal magnetic field will be provided by an energized coil threaded through the center of the spectrometer. The main detector will be located in an inactive iron mine in northern Minnesota, which is presently a state park. The detector will be located about 750m below ground at the distance of 730km from Fermilab (Fig. 1.3).

A smaller version of this detector will be located on the Fermilab site, about 250m downstream from the end of the hadron decay volume. The presence of neutrino oscillations would reflect itself as a difference between (appropriately normalized) rates, energy spectra, and flavor composition of the observed events at the two sites.

The expected event rate in the main MINOS detector ranges from 500-3000 events/kt$\times$yr, depending on the energy tune of the beam. The comparison of charged current events rate and energy distribution in the two detectors will be sensitive to oscillations at the level of 4σ over the full parameter space currently suggested by Super-K experiment, as shown in

Fig. 1.4

MINOS will make a step beyond the observation of the oscillations, it will also provide a precise determination of the oscillation parameters. Fig. 1.5 shows the expected precision of this determination for three values of Δm^2.

A very important measurement is the determination of neutrino flavors involved in the oscillations. Because the Super-K experiment sees no anomalous behavior in ν_e interactions and the reactor experiment CHOOZ[17] sees no $\overline{\nu_e}$ depletion consistent with $\Delta m^2 > 10^{-3} eV^2$, the oscillations are likely to involve ν_μ's, but the Super-K experiment has not been able so far to discriminate between the hypotheses $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_{sterile}$. In the MINOS experiment, the former oscillation mode would deplete ν_μ CC interactions, give rise to ν_τ CC interactions and would leave the NC interaction rate unaltered. The latter mode would reduce both the CC and NC interaction rates.

The definitive way to identify the $\nu_\mu \rightarrow \nu_\tau$ transitions would be via observation of τ leptons resulting from ν_τ CC interactions. This is impossible on an event-by-event basis in a conventional detector like the MINOS spectrometer, since the typical τ decay path length at MINOS energies is of the order of several hundred microns. If Δm^2 is sufficiently high, $> 10^{-3} eV^2$, the two modes can be distinguished by a statistical test comparing the ν_μ CC to total NC rate. This measurement, however, becomes more difficult at lower energies (needed to probe the lower Δm^2 region) because of the difficulty of NC/CC separation and potential trigger systematics.

In general, the oscillation pattern may be more complicated and it may involve a combination of $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_{sterile}$ transitions.

We desire to extend the MINOS physics reach to improve neutrino flavor identification capabilities by constructing a hybrid emulsion detector (HED) in front of the main spectrometer. Such a detector will allow unambigous identification of τ's from ν_τ interactions and electrons from ν_e interactions. Nuclear emulsion is the only practical medium known today which has sufficient spatial resolution to accomplish that. Construction of such a detector, however, with sufficiently high target mass and at reasonable cost, presents formidable challenges.

1.3 Evolution of Emulsion Experiments in High Energy Physics

Emulsions have played a key and pioneering role in the early days of particle physics. Many of the long lived "elementary particles" were discovered using emulsion technology and their principal properties have been elucidated using this technique. The 60's and 70's saw a decline in the popularity of emulsions in particle physics, as more powerful and more versatile detectors were developed and the energy frontier shifted to the colliding beam experiments, which are ill-suited to the use of emulsions.

In the last 25 years an important new niche opened up for emulsions in High Energy Physics (HEP) with the discovery of short lived particles (charm, beauty, and tau) with lifetimes in the 0.1-1 picosecond range. The superior spatial resolution of emulsions, of the order of a fraction of 1 μm, provided an important and unique experimental capability in the general arena of the study of production and decay of these particles. The fundamental limitation of the emulsion technique is the very labor-intensive scanning effort required to find and measure events. This has been partially alleviated through the addition of complementary detectors, allowing one to locate approximately the events in emulsion, and through advances in the automatic scanning of emulsions under computer control.

Neutrino physics provided an especially fruitful area for unique large scale experiments using emulsions. The first direct observation of a charmed particle was achieved in an experiment at Fermilab using an emulsion target[18]. More recently, the focus of efforts has shifted to investigations attempting to find, identify, and measure ν_τ interactions. Tau neutrinos produced in the beam dump via decay of D_s mesons are currently being studied in the DONUT experiment[19] at Fermilab. Oscillations of ν_μ's into ν_τ's over a short baseline have been the object of an intensive ongoing effort, initiated originally with the Fermilab E531 experiment[20] and continuing through the recently concluded CHORUS experiment at CERN[21].

To achieve its full potential sensitivity the CHORUS experiment, utilizing an emulsion target of almost 1 t, will have to scan and process about 1 million events. The interactions have to be found and examined for possible kinks signifying τ production and decay. This task has been made possible by inclusion in the apparatus of a sophisticated tracking system downstream of the emulsion and by the use of a fully automated scanning and measuring system.

The technological progress achieved in the CHORUS and DONUT experiments gives one confidence that ambitious emulsion detectors for long baseline neutrino oscillation experiments can be built. The long baseline experiments, however, present important new challenges.

1.4 Emulsion for Long Baseline Experiments

Design and construction of a successful long baseline neutrino oscillation emulsion experiment for detection of oscillations into ν_τ's presents a number of new challenges. We enumerate them briefly below:

- To achieve the required sensitivity, the target mass must be 2-3 orders of magnitude greater than that used in the most ambitious previous experiment, CHORUS. This necessitates a hybrid detector with separated functions: heavy and cheap material, e.g. lead, as a production target and emulsion as the τ decay detector.

- Even with the hybrid detector, the amount of emulsion required will be significantly larger than in CHORUS. This presents new engineering challenges connected with the necessity of mass production as well as the need to develop highly cost effective emulsion.

- The requirement of the large overall target mass implies that a sophisticated tracking system after each layer of emulsion cannot be afforded. Thus some degradation of the track localization information in the tracking system must be accepted.

- The last point implies that the scanning algorithm may have to be significantly different from that used in CHORUS.

There are, however, compensating effects which alleviate somewhat the potential difficulties enumerated above. In brief they are:

- The number of events to be scanned is expected to be significantly smaller, some 2-3 orders of magnitude less than in CHORUS. Thus more time consuming scanning procedures are acceptable.
- The small number of events (few/day) implies that data processing can be done almost in real time. One can construct a highly modular detector and periodically extract (and replace), develop, and scan only those modules where an interaction took place.
- The environment in the Soudan mine, deep underground and far from the accelerator, gives promise of background free emulsion. This would allow use of cheaper emulsions (fewer developed grains per track would be sufficient) and easier scanning.
- The fact that the required latent image lifetime is only of the order of a week or so, implies that emulsion with properly tuned fading properties may be attractive and would facilitate scanning.

The goal of the proposed R&D program, described in this document, is to find optimum solutions for the required detector in light of all of the above considerations.

1.5 Physics Capabilities of the MINOS HED

Our goal is to construct a hybrid emulsion detector with a total mass close to 1 kt. We feel that such a goal is realistic if the outlined R&D program will be able to succeed in addressing adequately the challenges discussed above. Possible arrangements of the detector will be discussed in detail in the rest of this document. Here we only summarize the most fundamental concepts.

The basic building block is a micromodule consisting of a thin (about 1mm) sheet of lead (serving as potential target) followed by two layers of emulsion, each layer of sufficient thickness to identify tracks and measure their direction with sufficient precision. The emulsion layers are separated by a thin (about 1mm) layer of inert, light material.

Tau leptons, produced in the lead, would be identified in two different ways. The cleanest signature would a significant kink in the particle trajectory, in case of a decay in the inert layer between the emulsions. Taus decaying in the lead can be identified through a finite impact parameter of their decay products. We expect total detection efficiency to be in the 25-50% range.

Besides its unique capability as a τ lepton detector, such an HED would also be a powerful ν_e detector. A potentially very important measurement is that of the $\nu_\mu \to \nu_e$ oscillation probability at the Δm^2 in the range of atmospheric neutrino oscillations. This probability is expected to be small and thus would be difficult to measure in the presence of large $\nu_\mu \to \nu_\tau$ oscillations because of the significant background due to $\tau \to e\nu\nu$ decays. Ability to identify whether the electron comes from the primary event vertex will allow significant suppression of the $\tau \rightarrow e$ background The efficiency for detection of ν_e's should be close to 100%.

We have calculated expected τ production rates through $\nu_\mu \rightarrow \nu_\tau$ oscillations for a 1 kt×yr exposure in a NuMI beam for different oscillation parameter hypotheses. Fig 1.6 shows the equi-production contours for ν_τ's in the oscillation parameter space. They have to be multiplied by the detection efficiency and the exposure time to obtain the observed number of τ events.

For the currently preferred set of Super-K parameters ($\sin^2 2\theta = 1$ and $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2) the proposed MINOS HED would allow us to observe a significant number of ν_τ's and to achieve sensitivity for oscillations into ν_e at the level close to 1%. The ultimate sensitivity of a several years long exposure extends down beyond $\Delta m^2 \approx 1 \times 10^{-3}$ eV^2. For Δm^2 values below 5×10^{-3} eV^2, the number of expected ν_τ events is proportional to the product $\sin^2 2\theta \times \Delta m^2$. Thus a comparison of the observed number of events in the HED with the rate predicted from the energy spectrum measurements in the main detector, will allow one to set limits on a possible $\nu_\mu \rightarrow \nu_{sterile}$ oscillation component.

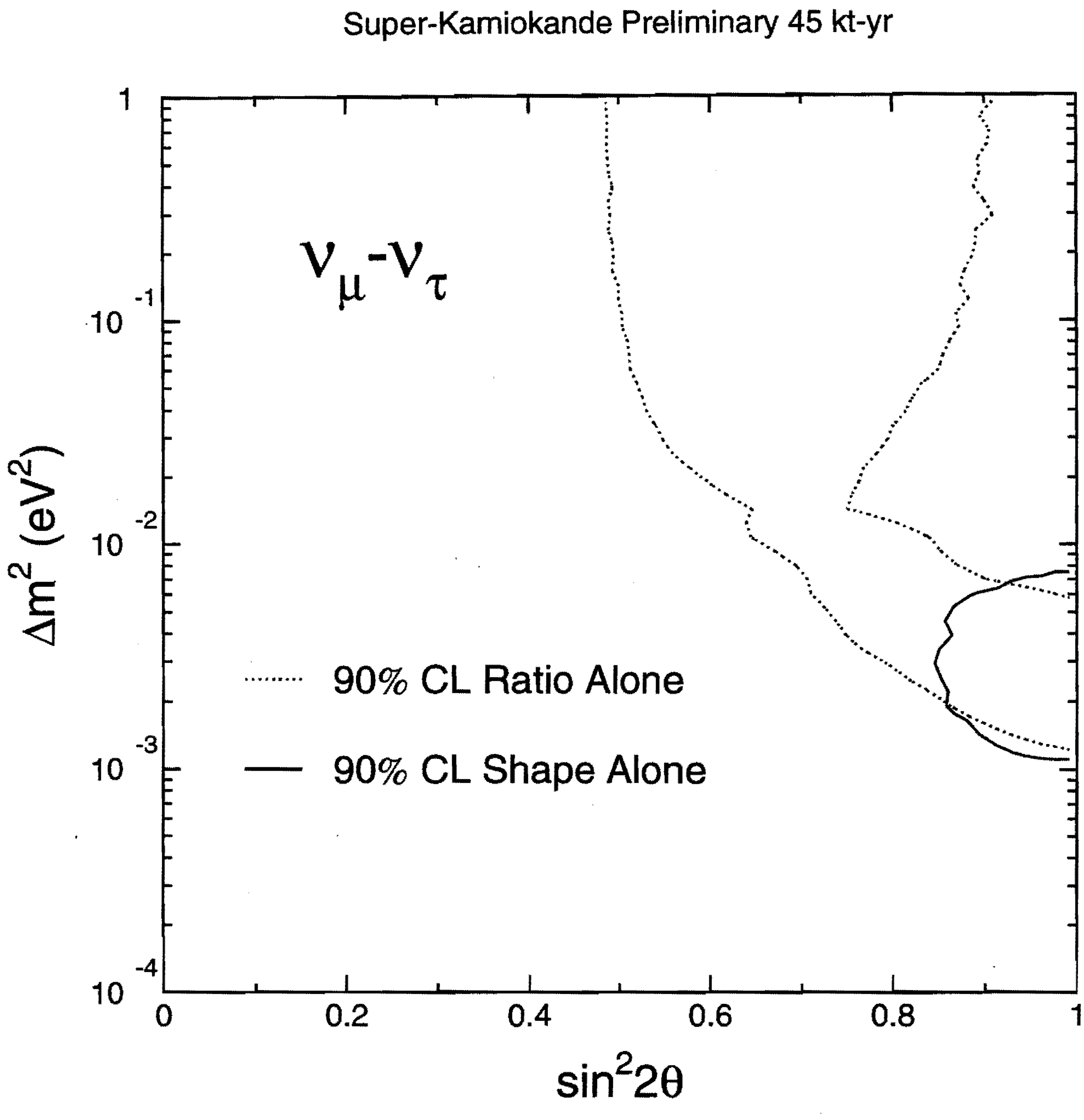

Figure 1.1: SuperKamiokande fit of the neutrino oscillation hypthesis

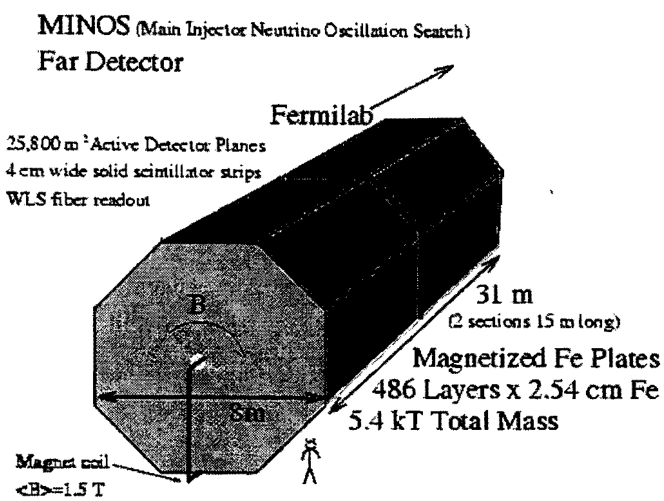

Figure 1.2: MINOS detector: overview

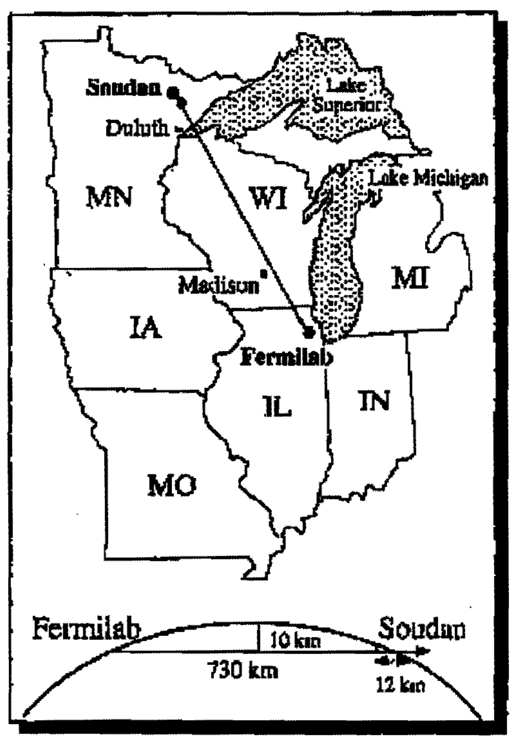

Figure 1.3: Geographical layout of the MINOS experiment.

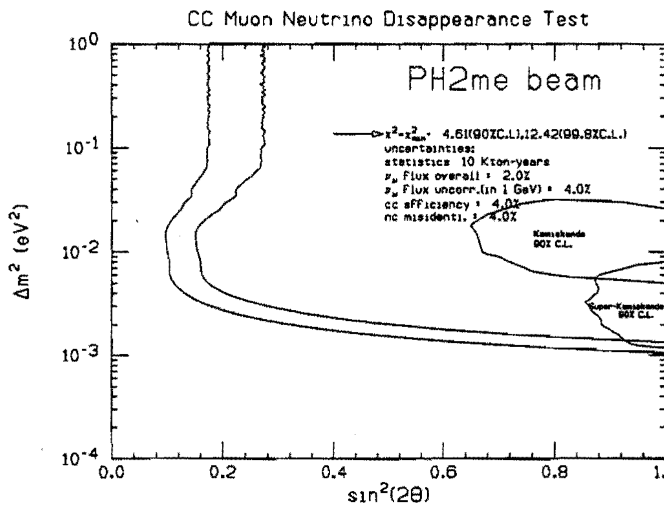

Figure 1.4: Sensitivity of the disappearance experiment using medium energy beam

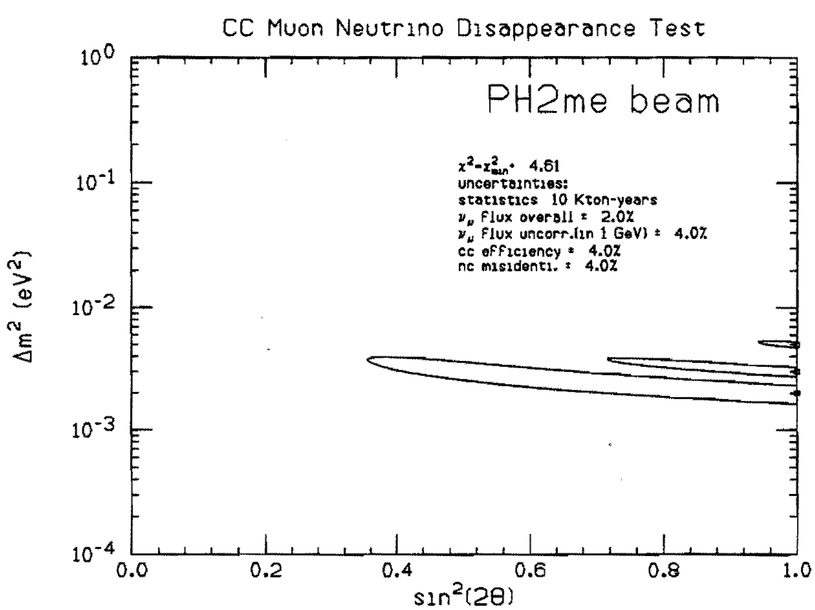

Figure 1.5: Expected precision of the determination of the oscillation parameters in the disappearance experiment in medium energy beam

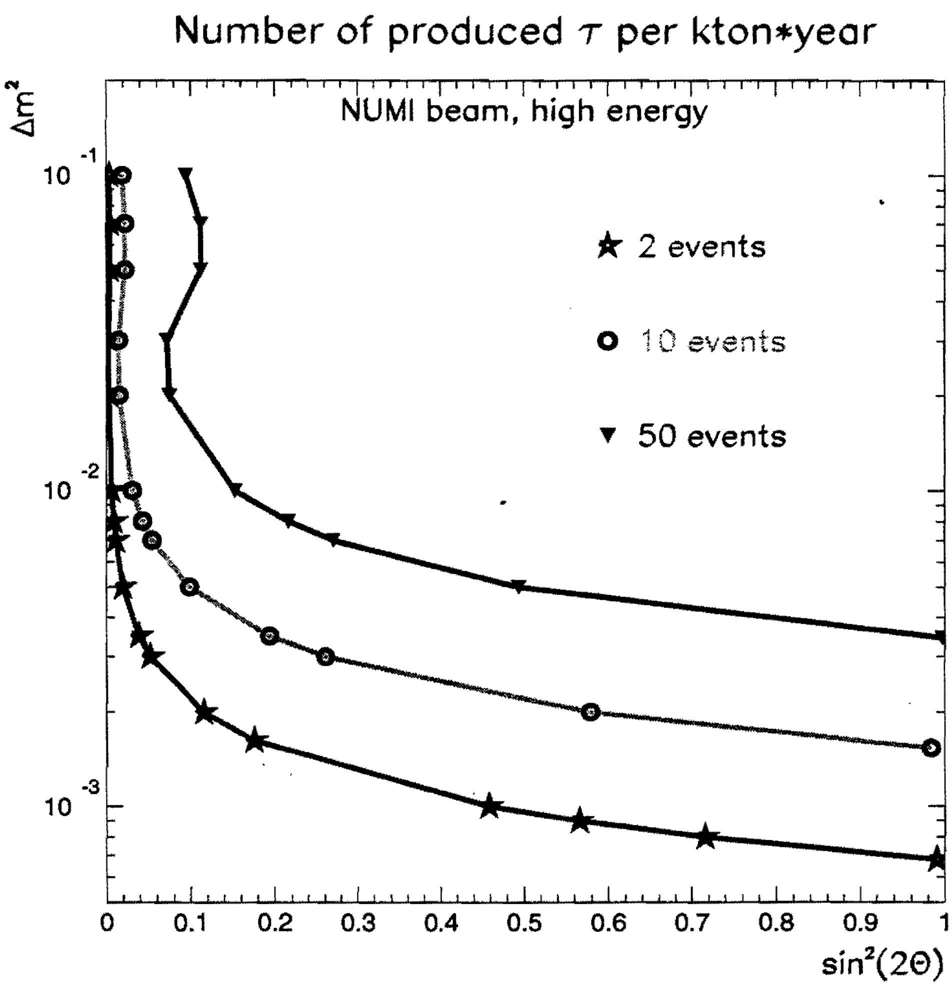

Figure 1.6: Expected rates of tau production as a function of the oscillation parameters

Chapter 2

Photographic (Nuclear) Emulsions

2.1 Principles of the photographic process

Photographic emulsions are commonly used to detect photons of visible light or X-rays to register images. The detecting medium consists of crystals of $AgBr$ interspersed in gelatin. Sizes and shapes of $AgBr$ vary depending on application, but typicaly sizes range from 0.2 to several microns. Absorption of photons by the crystal or the passage of a charged particle leads to the creation of electron-hole pairs within the crystal. Electrons migrate to the traps located at the surface of the crystals; subsequently interstitial silver ions migrate to these traps, recombine with the electrons and become neutral atoms of silver. A cluster of four or more silver atoms is stable and it constitutes a 'latent image center'.

The development process consists of two fundamental stages: development and fixing. In the former stage, the developing agent (in particle physics applications typically amidol) reduces silver ions in a crystal to neutral silver atoms. The resulting clump of silver is observable as a dark 'grain'. A cluster of four or more silver atoms (latent image center) acts as a catalyzer of this process, thus distinguishing 'hit' crystals from the rest. In the fixing process the remaining, unreduced crystals of $AgBr$ are dissolved and subsequently washed away from the emulsion.

Optimization of the photographic emulsion for a given application usually requires an improvement of the efficiency of the formation of the latent image centers. This is achieved by doping the crystals to create electron traps as potential sites for the image centers, creation of hole traps to reduce recombination, and optimization of the crystal morphology: shapes, sizes, lattice imperfections. The development process is catalyzed by a cluster of four silver atoms, but gold atoms can play the same role. The newest sensitization method consists therefore of implanting electron traps on the surface of the crystal and deposition of one or two gold atoms in these traps. Such crystals have much higher sensitivity as fewer silver atoms are necessary for the latent image formation.

2.2 Production and properties of photographic emulsions

Production of the photographic emulsion consists of three principal stages:

- precipitation of $AgBr$ crystals in a water solution of gelatin. In this stage the reactants, $AgNO_3$ and KBr (or NH_4Br), are pumped into a vessel containing the gelatin solution. Flow control of the reactants according to the concentration of Ag and Br ions in the solution, as well as the control of the stirring conditions allows precipitation of $AgBr$ crystals of well defined shapes and sizes

- washing of unwanted salts. In this stage the reaction by-products (KNO_3 or NH_4NO_3) are washed away from the solution.

- sensitization. Pure, undoped $AgBr$ crystals exhibit low sensitivity. In the sensitization stage they are doped with sulphur (Ag_2S was found to create efficient electron traps), gold, stabilizing agents etc.. This stage increases the photographic sensitivity by a factor of fifty or more.

Nuclear emulsions produced in the early days of this technique exhibited variable sensitivity, usually related to the properties of the gelatin used. Anecdotal relation of the quality of the emulsion to the diet of cows used to produce gelatin can be understood in terms of the sulphur content of the gelatin, thus acting as a sensitizing agent[27]. Establishment of the photographic, inert emulsion standards by the photographic industry [28] and controlled sensitization in the production process were important steps toward achieving reproducible, high quality photographic emulsions.

Although detection of charged particles by a photographic emulsion is very similar to an image registration by a photographic film, there are several important differences. Creation of electron-hole pairs in an $AgBr$ crystal by visible light photons differs from pair creation by traversal of a charged particle. Particle detection by a crystal requires that the latent image center is created, with high efficiency, during the traversal of a single particle, whereas in photography several photons per crystal are needed to create an image. High sensitivity photographic films employ large area crystals, thus increasing the captured photon flux, whereas particle detection is governed by the volume effect (track length within the crystal). These and other factors, related to the geometry of the detecting layers, distinguish production of 'nuclear' emulsion from the 'photographic' or 'X-ray' emulsion. These differences are particularly important where efficient detection of minimum ionizing particles is required.

From the particle detection point of view, emulsions can be characterized by their sensitivity, random noise density and the latent image lifetime. Sensitivity of the emulsion is usually expressed in a number of visible silver grains per 100μm of a particle track. Typically, good quality emulsion produces 35-40 detectable grains per 100μm, although emulsions with grain counts exceeding 50 have been produced by several companies. It is important to remember that emulsion shrinks by about a factor of two during the processing. As a result, the grain density becomes anisotropic, and it increases by a factor of two in the direction perpendicular to the base. Grain densities for relativistic particles are typically quoted for the direction parallel to the base. Random noise, sometimes called fog, is related to the $AgBr$ crystals which have been reduced to silver grains by the developer without the help of a catalyzing latent image center. The fog density is usually expressed in a number of developed grains per $1000\mu\text{m}^3$ of the emulsion. Typical fog level is of the order 2-4 grains. Effective sensitivity and fog level depend somewhat on the details of the processing method:

longer development increases somewhat the number of detected grains along the track, at the same time increasing the number of random grains.

2.3 Detection of Charged Particles Using Photographic Emulsions

Nuclear emulsions have been used for particle detection for the past 50 years, yielding several discoveries and important measurements[29]. The chief advantages of this technique are its excellent spatial resolution and granularity. The main disadvantage of nuclear emulsion is the lack of time resolution, leading to accumulation of signals over the lifetime of the experiment. A former disadvantage, related to the slow and manpower-intensive analysis process, has been practically eliminated by the rapid progress of computerized image acquisition and image processing techniques.

Nuclear emulsions are used in experiments in the form of thin layers, usually attached to a plastic base. The thickness of the emulsion layers used in experiments varies from $50\mu m$ to some $600\mu m$. There are two typical geometrical arrangements of the emulsion:

- 'parallel', where the beam of particles is more or less parallel to the plane of the emulsion layer
- 'perpendicular', where the particles to be detected cross the emulsion layers at very large angles, nearly perpendicular to the plane of the emulsion.

After the exposure and subsequent processing, the emulsion plates are analyzed with scanning microscopes. Typical objectives used for scanning have a magnification of $\times 20 - \times 50$. At these magnifications the effective depth of field is of the order of $3\mu m - 7\mu m$. Traditionally, these images were scanned by dedicated scanning staff. Nowadays, they are typically acquired with a CCD camera and subsequently digitized using frame grabbers. The effective field of view is determined by the size of the CCD chip and the magnification of an objective. Using a standard 1/3" CCD camera, with 512×512 pixels, a volume of the order of $100\mu m \times 100\mu m \times 3\mu m$ can be analyzed, with a pixel resolution of $0.2\mu m$ when a $\times 50$ objective is used.

In the early emulsion experiments the emulsion stacks were usually exposed in the parallel fashion. Charged particle tracks, easily visible within a single field of view, were followed throughout the emulsion volume.

In recent years emulsions have been predominantly used as planar tracking detectors, with tracks intersecting the emulsion planes at large angles[36, 21, 19]. In this geometry, track detection and analysis requires that the image information from several layers of the emulsion be combined. Automation of the image acquisition and digital image processing using computers have greatly improved the speed and reliability of analyzing emulsions. Scanning time is significantly reduced by using external tracking information, from such devices as scintillating fiber trackers or X-ray films.

The tracking information obtained from the emulsion layer is similar in nature to the information obtainable from other tracking devices, e.g., silicon detectors. However, the high spatial granularity of the emulsion leads to two important advantages over other tracking detectors:

- track direction can be measured in addition to the position information, even in relatively thin emulsion layers
- track trajectory is sampled every few microns, hence decay kinks can be detected even for very short lived particles.

2.4 Construction of detectors

Historically, many physics collaborations have produced their own emulsion detectors, using relatively thick emulsion layers on plates of relatively large dimensions. The comparatively small volume of previous detectors and configuration of the plates meant that this could be accomplished by individually producing and installing each sheet by hand. For the detector under consideration here, this is not practical. Nonetheless, the basic steps are the same regardless of whether the plates are hand made or mass produced:

- pouring the emulsion onto a prepared plastic base
- drying of the liquid emulsion
- assembly of the emulsion plates into the detector

2.4.1 Pouring of emulsion plates

Emulsion in gel form is stored in a dark and cool environment. Before the pouring it is warmed up to a temperature around 45^oC to lower its viscosity to a level around 10 cP. This liquid is poured onto a prepared plastic base and subsequently distributed uniformly over the entire area of the base. At this stage water constitutes about 90% of the volume of the emulsion, hence the thickness of the liquid layer is ten times larger than the final thickness of the dry emulsion layer. To ensure the uniformity of thickness of the final emulsion layer it is essential that the surface of the plastic base be horizontal, with an accuracy of the order of $1mrad$. Both sides of the plastic base are usually coated with the emulsion. This is achieved by drying the emulsion poured on one side and subsequent coating of the other side.

The choice of the base plastic is very important: it must possess the necessary mechanical stability and provide adequate optical properties. Polystyrene and acrylic plastics are often employed. Tri-acetate cellulose or polyesters, used by the photographic industry, are not adequate for high energy physics applications. The former doesn't have adequate mechanical strength; the latter is bi-refringent, making it very difficult to observe the emulsion grains through the plastic base.

Plastics, as bases to be coated with nuclear emulsions, present two difficult problems, related to their surface properties:

- plastics have large surface energy, they are hydrophobic. This property makes it difficult to spread liquid emulsion over the surface of the base

- non-wettable materials are also non-bondable, most of common adhesives do not bond very well to plastic surfaces. This problem is of particular importance as the nuclear emulsion undergoing the photographic processing spends a long time in the water environment.

Plastic bases used for coating with the emulsion must be properly pre-treated, either chemically or physically to alter their surface properties. This treatment usually consists of surface cleaning, oxidation of a polymer, providing functional bonding sites and grafting of specific radicals onto the polymer backbone. Preparation of the plastic base is a very important step and is a well-guarded trade secret. Usually, pre-treated plastic bases for use in high energy physics are provided by the photographic industry.

2.4.2 Drying of the Coated Emulsion Plates

Liquid emulsion, poured onto the plastic base, gels very quickly once its temperature drops below 25^oC. At this stage it can be safely transferred to the drying cabinets, where most of its water content will evaporate.

Drying of the emulsion proceeds in a dark, well-controlled environment. A laminar flow of clean air with relative humidity about 75% and temperature about 25^oC is usually quoted as a necessary condition. It takes typically some $15 - 20$ hours to dry the emulsion to the final thickness of 100μm.

During the drying stage the effective volume of the emulsion is reduced by a factor of ten, it is therefore of utmost importance that the drying process proceeds very uniformly throughout the entire volume. Drying too rapidly will lead to the formation of a 'skin' at the surface of the emulsion, which will significantly hamper the drying below the surface. Non-uniform drying of different areas of the emulsion (caused, for example, by a gradient of the relative humidity over the surface) may lead to lateral displacements of the gelatin and may cause significant distortions in the processed emulsions.

After drying of the first emulsion layer, the plate is returned to the coating station, where the other side of the base plate is coated and subsequently dried.

2.4.3 Assembly of the Emulsion Plates into the Detector

High energy physics experiments usually require assembly of several emulsion plates. They sometimes need to be cut to the required size, have alignment holes punched or be machined to required sizes/tolerances. Naturally, all these steps need to be performed in the dark, with only red safety lights.

Typically, the detectors consist of a sandwich assembly of emulsion plates alternating with spacers or layers of heavy metals. Photographic emulsion is very reactive: it may corrode materials with which it comes in contact, usually degrading its own photographic sensitivity. It is therefore very important that only nonreactive materials come into direct contact with the emulsion. Some grades of stainless steel, silver, plastics and glassine paper are common examples. For a detector with alternating lead and emulsion layers, the lead may be coated with an acrylic layer, or a protective layer of glassine paper may be used.

When particle trajectories cross several emulsion layers, it is important to maintain relative alignment of the emulsion plates within the detector. Several methods have been previously employed for this purpose. Precision machining and fiducial marks made with radioactive sources are among the most frequently used methods. For a large detector consisting of 8 million layers, such methods may be impractical or cost-prohibitive, or both, and different methods may need to be explored. The precision requirements for the alignment will depend on the background conditions as well as on the final analysis techniques.

To preserve the emulsion sensitivity over a long period of time and to avoid the latent image fading it is usually necessary to provide a controlled environment for the emulsions. Usually the emulsion detectors are contained in an evacuated container at a temperature of the order of 5^oC.

2.5 Optimization of the Nuclear Emulsion

A long baseline neutrino oscillation experiment requires a very massive detector. Since the cost of emulsion is likely to be the driving factor for the cost of the detector, it is very important to explore possible avenues of minimizing this cost.

Several aspects of a long baseline oscillation experiment are very similar to previous experiments with cosmic rays or short baseline oscillation searches. These similarities allow for a simple extrapolation of the detector performance and detection efficiencies, as the fundamental geometry of the detectors is very similar. On the other hand, there are important differences between these experiments, opening new possibilities for the optimization of the emulsions. The chief difference is related to the environment of the detector.

In cosmic ray experiments, emulsions are exposed to a very intense flux of charged particles and gamma rays in the upper atmosphere. In accelerator experiments, background muon fluxes integrated over the lifetime of the experiment may approach $10^5 particles/cm^2$ of the emulsion. Muons and Compton electrons from the cosmic ray background, as well as any ambient radioactivity, must be added to this.

This is in stark contrast to the proposed experiment in the Soudan mine: there are no background muons at all from the accelerator and the cosmic ray background is attenuated by a factor of 10^5. We therefore expect that the background in the emulsions will be several orders of magnitude smaller than in previous experiments. It will probably be dominated by the Compton electrons induced by γ rays from radioactivity of the rock, lead plates or perhaps the emulsion itself.

Nuclear emulsion used in experiments offers very high detection efficiency and very large rejection power against background. This is achieved by a very high density of developed silver grains along the trajectory of a minimum ionizing particle. A yield of some $35 - 40$ grains per 100μm of track length is typical. We expect that in the radiologically clean environment of the Soudan mine we can ensure adequate detection efficiency and measurement accuracy with much fewer grains of silver, perhaps around $15 - 20$ grains. Such an emulsion would require much lower silver content, thus leading to significant reduction of the cost of the experiment.

Studies of emulsions diluted with gelatin were carried out by Ilford[37] 50 years ago, and more recently at Nagoya University[38]. These studies indicate that the reduction of the number of grains per unit length of track is somewhat slower than the reduction of the silver content of the emulsion. This can be understood in terms of a sensitizing effect of the gelatin (or perhaps some of its components). These studies indicate that dilution by a factor of at least three should be achievable, while maintaining excellent detection and measurement capabilities of the emulsion.

A possible avenue for taking advantage of the low background conditions is to erase the latent image present in the emulsion before installing it in the detector. This can be achieved by chemical or physical means of destroying the latent image centers, the simplest method consist of exposing the emulsion to very warm and moist air. An attractive option is an emulsion with a finite and controlled 'memory time' of the order of one month. Such an emulsion, processed shortly after the interaction took place, would only contain the background accumulated over this relatively short period and would thus offer the greatest opportunity for optimizing the silver content.

2.6 Systematic Errors in Measuring the Angle

Tau identification in the long baseline neutrino oscillation experiment will require highly efficient detection and good angular resolution of very short track segments. In principle, it can be easily achieved within a single layer of emulsion, with thickness of the order of $100\mu m$.

Assuming 'optimized' emulsion with $15-20$ grains per $100\mu m$ of track and, assuming further that at least 5 co-linear grains are necessary to define the track, overall track detection efficiency should exceed 99%.

The expected angular resolution is

$$\Delta\theta = \frac{\Delta x}{t}\sqrt{\frac{12N}{(N+1)(N+2)}}$$

where Δx is the position determination error, t is the emulsion thickness and N is the number of measured, equidistant points. With sub-micron precision of the position determination of a grain, the expected accuracy of the angle measurement in a single $100\mu m$ layer is of the order of a few milliradians. Such an angular resolution would be quite adequate for τ identification, as we expect to detect decay kinks in excess of $50mrad$.

It is very likely, however, that the angular resolution will not be limited by measurement errors of a statistical nature, but rather by various systematic effects. Possible distortions of the emulsions are the primary source of such effects.

When a charged particle crosses emulsion, it leaves a trace of 'hit' $AgBr$ crystals. These crystals determine the original particle trajectory with an accuracy of the order of $0.2\mu m$. There are several reasons why the silver grains observed under the microscope are displaced from their original position:

- during the photographic processing the emulsion swells by a factor of three, some of the grains may undergo lateral displacement
- during the fixing process a significant fraction of the volume of the emulsion is washed away. The collapse of the resulting voids may lead to some lateral displacements

- the emulsion (gelatin) may have some internal stresses induced in the drying process. These stresses, relaxed during the wet phase of the processing, may lead to some lateral displacements.

These and other factors may cause some distortion field to be present in the emulsion. These distortions will, in general, leave unchanged the position of grains in the immediate vicinity of the plastic base and will preserve the original angle of the track near the surface of the emulsion.

These distortions must be determined and calibrated out to achieve the ultimate angular resolution of the emulsion. Calibration of the distortions can be achieved with the help of tracks observed on both sides of the plastic base: points adjacent to the base determine the true track trajectory, whereas the displacements of the actual grains from this trajectory measure the local distortions of the emulsion.

Another factor relevant to the angular resolution is related to the shrinkage of the emulsion as a result of washing away the undeveloped crystals of $AgBr$. This shrinkage is approximately a factor of two (less if the emulsion is diluted, as a smaller fraction of its volume is occupied by $AgBr$). As a result, all angles measured in the processed emulsion need to be corrected by a shrinkage factor. Systematic error in the measurement of the shrinkage will therefore contribute to the overall systematic error of the angular measurement.

Chapter 3

Detector Design Considerations

3.1 Physics consideration

Our motivation for constructing the hybrid emulsion detector (HED) is to acquire a capability of detecting $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ oscillations through the unambiguous detection of either τ leptons or primary electrons.

3.1.1 Signal Rates

Rates of the observed CC ν_τ interactions relative to those of the dominant ν_μ interactions depend on the oscillation parameters. The ratio of the CC event rates $\rho = N(\nu_\tau)/N(\nu_\mu)$ is given by

$$\rho = \eta \sin^2 2\theta \sin^2(\frac{1.27L\Delta m^2}{E_\nu})$$

where η is an energy dependent ratio $\sigma^{CC}_{\nu_\tau}/\sigma^{CC}_{\nu_\mu}$.

For relatively low values of Δm^2, i.e. $< 5 \times 10^{-3} eV^2$, $\sin^2(\frac{1.27L\Delta m^2}{E_\nu}) \approx (\frac{1.27L\Delta m^2}{E_\nu})^2$ and the ratio ρ depends on Δm^2 through $\rho = \eta \sin^2 2\theta (\frac{1.27L\Delta m^2}{E_\nu})^2$. To detect $\nu_\mu \to \nu_\tau$ oscillations corresponding to the best Super-K values of $\sin^2 2\theta = 1$ and $\Delta m^2 = 3.2 \times 10^{-3} eV^2$, and our length $L = 730km$, the optimum beam energy would be about 10 GeV. At this energy $\eta \approx 0.2$, giving $\rho \approx 0.02$.

In the case of $\nu_\mu \to \nu_e$ oscillations there is no kinematical suppression and the observed rate of ν_e interactions will be a factor of 5 higher, or $\rho \approx 10\%$. On the other hand, the corresponding mixing angle is likely to be much smaller, thus reducing the observed ν_e interaction rate to be somewhere below 1% of the ν_μ interactions. At low Δm^2 the ultimate sensitivity of the experiment will therefore be limited by fluctuations of the ν_e component of the beam.

3.1.2 Tau Identification

The unique signature of the τ lepton is its large angle decay close to the production vertex. Such a decay can be identified in two distinct ways: either by observing the decay kink itself by measurement of the τ direction before its decay and and the direction of its decay products, or (if the τ is not observed directly) by measuring the impact parameter of the τ daughter track at the vertex. The conventional impact parameter method is feasible only if the vertex can be defined by the presence of two or more charged primary tracks originating from the neutrino interaction. If there is only one primary track, the τ signature would be a finite distance of closest approach between the primary track and the τ daughter.

3.1.3 Conceptual Detector Design

For economic reasons one needs to separate the target and measurement (i.e., emulsion) sections. In this way one can increase the total detector mass cheaply by using the highest economically feasible density material for the target, probably lead. In this approach, the detection technique will be most efficient and the observed signal most background free if one can measure the event as close to the interaction point as possible. Since a typical pathlength for a 10 GeV τ is about 500 μm, this sets the scale on the target thickness as 1mm or less, implying a detector structure composed of alternating layers of target and emulsion layers.

For the identification of ν_e events the same general considerations apply. We want to see and measure the electron track before the shower develops so that we can measure the direction of the electron. This calls for minimizing the number of radiation lengths between the production and measurement points.

3.2 Background Considerations

An optimized detector will minimize the number of backgound events while maintaining a high number of detected events.

3.2.1 Backgrounds to ν_τ detection

3.2.1.1 Charm Production by ν_μ CC events

Charm particles have a lifetime comparable to the τ leptons, $c\tau$ of the $D^{\pm}$ being 314 μm and that of the D^0 124 μm (as compared to 87 μm for the τ). The charged D's can thus fake τ's in both identification techniques discussed above; the neutral D's can mimic τ's in the impact parameter method.

A very significant rejection factor against charm can be achieved by detection of the presence of a primary muon in ν_μ CC events. This handle will not be present for the NC events with $c\bar{c}$ pair production, but one expects that process to be strongly suppressed at our energies.

Information on charm production in ν interactions is available from the CDHS[23] and CCFR[22] experiments, but only above E_ν =30 GeV. For lower energies less extensive information exists from bubble chamber work at Fermilab[24],the CERN SPS[25] and the CERN PS[26]. Based on these data one can expect that at our energies charm production in CC events will be somewhere between 10^{-3} and $10^{-2}$of the total cross section.

Understanding the charm background is an important part of the simulation work to be undertaken in our proposed R&D program. Here we limit ourselves to some rough estimates of this potential problem based on qualitative arguments. Charm particles will have a softer momentum spectrum than the τ leptons, which may roughly compensate for their longer lifetime and thus yield comparable detection efficiencies for charm and τ's. Using the cross section estimates above, we can expect a comparable number of identified τ leptons and charm mesons. The identification of the accompanying primary muon should suppress the charm backround significantly, probably somewhere between one and two orders of magnitude.

3.2.1.2 Nuclear scattering of charged particles produced in NC interactions

The nuclear interaction length in plastic is about 60 cm; in lead it is about a factor of 4 less than that. Thus in 1 mm of plastic the probability of a nuclear interaction will be about 10^{-3}. Since only NC will contribute significantly to this background ($\sigma^{NC} = \frac{1}{3}\sigma^{CC}$) and their mean multiplicity should be somewhere between 1-2 at these energies, the background appears small compared to the anticipated signal level. The impact parameter method is more susceptible to this background because of the higher scattering probability in the lead. Our proposed R&D program calls for measuring this scattering probability as a function of scattering angle for various materials using accelerator beams.

3.2.1.3 "Accidental" kinks

Our detector will reside in an environment of radioactive decays from various sources: target, emulsion, base plastic or the cavern walls. These decays can produce gamma rays, which may subsequently produce Compton electrons in the MeV and sub-MeV range. Accidental intersections of these Compton tracks with the tracks from neutrino interactions, coupled with potential tracking inefficiency, could simulate "kink" events. Rough estimates indicate that this is not a serious problem, but nevertheless our R&D program envisages measuring the Compton electron background in emulsion in a realistic experimental environment in the Soudan mine.

3.2.1.4 Large angle Coulomb scattering

We plan to make a cut on the minimum angle acceptable, probably around 50 mrad. That should suppress entirely the Coulomb background. This effect will also be measured in the accelerator tests discussed above.

Nuclear interactions and Coulomb scattering ere expected to produce negligible background when particles of sufficiently high momentum (say above 1 GeV) are considered, but very low momentum particles could present a more serious problem. We expect that particle momentum can be estimated with sufficient precision by measuring scattering angles in subsequent lead plates. We plan to verify this assertion by exposing emulsion and lead plate assemblies to low energy hadron beams.

3.2.1.5 Emulsion distortion

As is discussed in the technical sections on emulsion, there is considerable shrinkage of emulsion in the development process which could result in distortion. Our processing technology will try to minimize these effects but we can also calibrate them by exposing the emulsions just below the surface to cosmic ray muons immediately before their development.

3.2.2 Backgrounds to ν_e events

Backgrounds to ν_e events will be quite different from backgrounds to ν_τ events, since the electron identification does not rely on detection of a kink but rather on the observation of an electromagnetic shower originating at the vertex.

3.2.2.1 ν_e's in the beam

The ν_e component in the beam is estimated at about 0.6%. Their interactions constitute the fundamental limit to achievable sensitivity for $\nu_\mu \rightarrow \nu_e$ oscillations. Their level can be measured quite well in the near detector but the extrapolated far detector rate will have an intrinsic statistical uncertainty. Thus this background will probably set a limit of about 10^{-3} of the ν_μ CC rate. An improvement could be possible with the use of a narrow band beam.

3.2.2.2 Tau $\rightarrow$ e decays

This background will be suppressed by a factor of 5 (due to ratio of cross sections) $\times$ 6 (Branching fraction into e's) $\times$ another factor (3-5) due to the fact that electrons from the τ decays will not point back to the vertex. Thus the product of all three indicates that in the presence of $\nu_\mu \rightarrow \nu_\tau$ oscillations at the maximum mixing angle, a limit on the sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations lies somewhere around $\sin^2 2\theta = 0.01$. Further simulations will refine this crude estimate.

3.2.2.3 Dalitz pairs or conversions near the vertex

The electrons from this source will in general be quite soft compared to electrons from ν_e interactions. Simulations are required to obtain precise estimates and to develop cuts to reduce this background if necessary.

3.3 Overview of the Detector

Based on the considerations discussed above one can sketch the main features of the HED. We need to consider two scales, macroscopic (order of cm's) and microscopic (order of μm's). At the macroscopic scale, one uses electronic detectors to identify the presence of a neutrino interaction, determine the lead-emulsion module in which the event occurred, and pinpoint the location of that event to a small fraction of the module's volume. At the microscopic level, one uses the emulsions to actually locate the tracks, identify ν_τ and ν_e events, and measure them as completely as is required.

The density of electronic detectors is determined by a variety of factors. The main ones reduce to economics vs. precision. A reasonable compromise for the amount of material between electronic detectors is about 10 radiation lengths and less than an interaction length.

Assuming 50% lead by volume in the modules would give a spacing every 10-15cm. The electronic detectors would form planes covering the full detector. Ideally, one would want to achieve spatial resolution of close to 1mm and have two-dimensional readout in each plane. Proportional tubes or limited streamer tubes appear to be attractive candidates for this function.

The microscopic detectors would consist of layers of target material (Pb) alternating with the measurement layers. Logically the measurement layer would consist of a thin emulsion layer, sufficient to measure the direction, followed by the decay layer (probably thin plastic), followed by another emulsion layer. Various possibilities for implementing this logical structure are discussed in the subsequent section. This part of the detector would be subdivided transversely in both directions, yielding small modules (e.g., $10 \times 10 \times 10$cm) as the basic element of the microscopic detector. We want this detector to be modular so that only a small fraction of the emulsion would need to be developed whenever a trigger occurred.

3.4 Detector Optimization

The final optimum design geometry will depend upon several factors, some of which are relatively easy to fold into the calculation:

- cost of emulsion
- space available for the emulsion detector
- acceptance for τ lepton to traverse at least one emulsion layer

Other factors, however, which also impact the decision on the final design geometry will require a significant R&D effort to assess:

- emulsion plates production process
- efficiency for track finding in nuclear emulsion
- background from radioactive decays in the detector

Preliminary optimization studies indicate that lead and spacer thicknesses in the neighborhood of 500-1500 microns each will maximize the number of ν_τ events in our final data sample.

Given the available emulsion coating technologies, we find that two basic emulsion detector configurations are possible: thick base ($\approx$800 microns) and 'thick' emulsions ($\approx$100 microns), or thin base ($\approx$100 microns) and 'thin' emulsions ($\approx$50 microns). In the latter case a medium thickness plastic spacer would provide the decay space for taus.. Thick base coating is a labor intensive process, and requires construction of an emulsion coating "factory." It reduces, however, the number of different layers required. Thin base coating involves the standard mass production technique used in the consumer film industry. Three examples of possible detector configurations with similar total detector cost (assuming that it is dominated by the cost of emulsion) are shown in figure 3.1.

Options A and B show possible emulsion configurations for 1 mm thick target and spacer layers, and option C shows a possible configuration for 500 micron thick target and spacer layers. The emulsion must always be coated to a plastic "base" which has a relatively low density and thus serves as a relatively background free region for observing the τ lepton

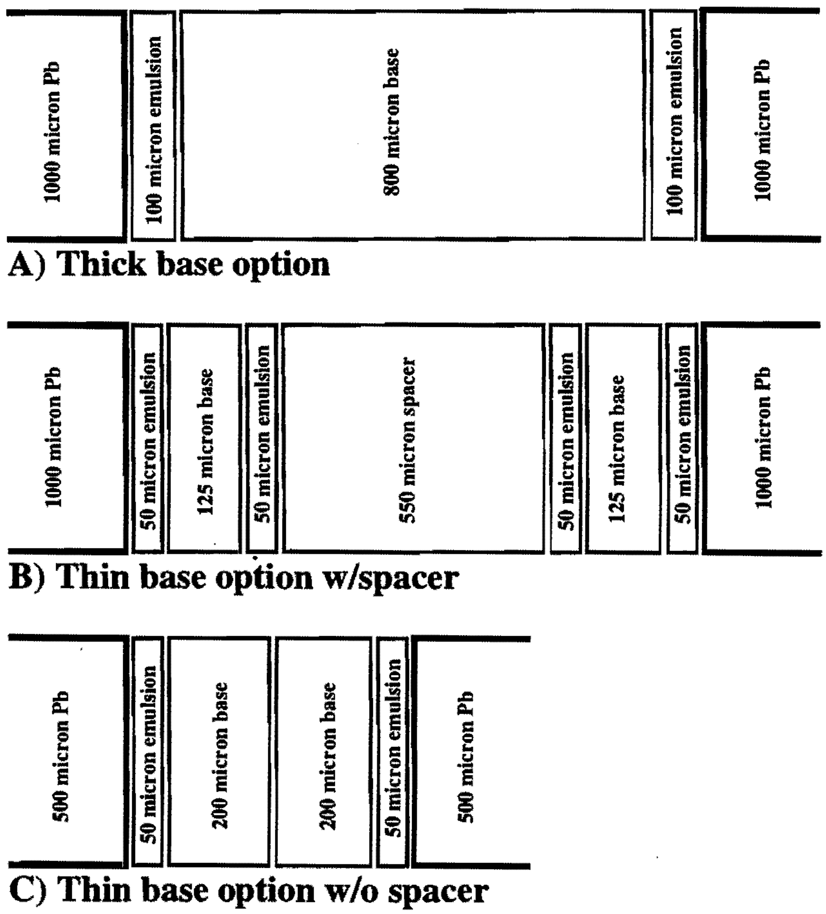

Figure 3.1: Examples of possible micro-detector geometries.

decays. In option B, an additional low density "spacer" must be introduced to increase the decay space.

Chapter 4

Reference detector

Even though the goals of our physics program with an emulsion detector are rather well defined, we are still far away from being able to design a credible detector which will do the required job. As a first step in this process it is useful to put forth a "straw-man" or reference detector which can be used as a basis for subsequent design studies. This chapter describes various components of such a reference detector.

We have already initiated detailed studies in a number of different areas to investigate in depth the proposed conceptual solutions. The results of this work are described in this chapter. Since we are still in the very early phases of our R&D program, the coverage so far has necessarily been incomplete and hence descriptions of different components vary significantly in the amount of provided details. We hope that the next year and a half of R&D will allow us to complete this process of understanding all the detector issues so that a credible conceptual design could be put forth at that time.

4.1 The trigger and event localization detectors

Planes of electronic detectors will be placed between the walls formed by the emulsion modules to determine that a neutrino interaction has occurred in the time gate of the neutrino beam generated at Fermilab. It is of vital importance that the electronic detectors identify with virtual certainty the particular emulsion module in which the event occurred since we intend to remove only the identified modules for processing. Beyond the identification of the correct module, the electronic tracking should significantly narrow the emulsion field that needs to be viewed by the microscopes thus substantially reducing the scanning time required to locate the event vertex.

The design of the experiment described here provides a narrow (2.5 cm) gap between the emulsion module walls for the electronic detectors. With this narrow gap it is not possible to measure the trajectories of the particles emerging from any particular emulsion module. Instead we use our electronic detectors to determine location of the event and the pattern of energy flow in the event across the various emulsion walls.

We expect that the principal background to our trigger will be cosmic ray muons. The cosmic ray muons generally give a predominantly vertical flow of energy whereas the flow of energy for the beam neutrino events is predominately horizontal. Furthermore the energy flow is aligned with the azimuthal direction from Fermilab so there is additional rejection ability. The combination of the short duty cycle of the neutrino beam and the known direction from the source provides a powerful rejection capability against cosmic ray background.

The emulsion modules are of the order of 10 cm by 10 cm by 10 cm. Thus the electronic detectors sample the event along the beam direction at intervals of roughly 10 cm. With this sampling interval we expect that a position measurement resolution of roughly 1 cm should be adequate to identify which particular emulsion module contains the event vertex. Most probably it will not be cost effective to improve the spatial resolution much beyond 1 cm because of the scattering and secondary particle production as the primary particles traverse the considerable amount of material (up to 5 cm of lead) in each emulsion module. However, for the neutrino interactions which produce muons, the benefit of 1 mm spatial resolution might will be worth the additional cost. Well defined muon tracks could considerably reduce the region in the emulsion that must be searched by the microscopes.

Other obvious requirements for the electronic detectors are high efficiency and long term reliability. Their large total area (about 2000 m^2) restricts the choice to mature technologies previously used in applications of a similar scale.

We consider "minidrift" tubes with anode wire and cathode strip readout (detectors similar to classic Iarocci tubes in their general design) to be the baseline option for the electronic detectors. The minidrift tubes consist of wires centered within 1-cm wide aluminum cells. One side of the cell is left open to allow for the measurement of the coordinate along the wire by the cathode strip readout. We anticipate that we will operate the tubes in proportional mode.

These types of detectors have been extensively used in high energy physics experiments for calorimetry and for tracking[30]. 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%. They are an attractive solution when a robust and inexpensive tracking detector is needed.

The minidrift tubes span the range of spatial resolutions that could be required for our application. With digital readout of the anode wires the detector resolution corresponds to the 1 cm cell size. The resolution is significantly better if the tubes are used in drift mode where a resolution of $0.3 - 0.5$ mm has been demonstrated [31]. There is a similar range of options for the cathode strip readout. By narrowing the strip width a resolution approaching 1 mm can be achieved. With digital readout the resolution is of the same order as the strip width. We will perform comprehensive simulation studies to understand our requirements for detector granularity and resolution.

Our collaborators at the Joint Institute for Nuclear Research (JINR) at Dubna have substantial experience in the construction of large systems based on this technology. JINR built Iarocci tubes for the DELPHI Hadron Calorimeter which have been successfully operated during the last 15 years at CERN. Recently minidrift tubes have been built as the forward muon tracking detectors for the D0 upgrade project[31]. The operation of Iarocci tubes in proportional mode (APTs) was one of the candidate technologies considered for the electronic detectors for the MINOS main detector and our collaboration has acquired a substantial amount of positive experience with these detectors.

The 2.5 cm gap width between the emulsion walls is sufficent for the installation of one plane of minidrift tubes. Both the anode wires and the crossed cathode strips are read out so we obtain position measurements for the two coordinates transverse to the beam using a single plane of tubes. The insertion of single planes of minidrift tubes between the emulsion walls might well provide an adequate electronic trigger and tracking system. We note that since a single minidrift tube does not measure the trajectory (only the x-y position) in any single gap we can not expect this system to determine the location of the event vertex within the identified emulsion module to an accuracy better than a few mm.

An alternate possibility for the trigger and event localization detectors is a pure scintillator system. The starting point for this design would be the same type of scheme of extruded scintillator strips with waveshifting fiber readout as used in the main MINOS detector except that the strip widths would need to be reduced to 1 cm.

4.1.1 The baseline minitube design

In the baseline design a single plane of minidrift tubes is inserted into each gap between the emulsion walls. Each plane is 5 m by 5 m to provide complete coverage of the emulsion modules. The full 1 kton emulsion detector requires 80 planes.

The planes must be modular in construction because of the need for their assembly in the cavern from pieces that can be brought down the Soudan shaft. A plane consists of 60 5-m long minidrift tube modules mounted transversely onto a series of 5-m long boards on which the cathode strips are affixed. The cathode strip width is approximately 1 cm so there are roughly 500 cathode strips for each plane. The overall thickness of a plane is 1.5 cm.

The minitube modules are similar to the MDT chambers for D0 and the APT planes of the MINOS calorimeter prototype. In the proposed design the individual module has 8 cells of 9.4 mm $\times$ 9.4 mm internal cross section with a 50 μm diameter W-Au anode wire strung at the center of each cell as shown in fig. 4.1. The cells are commercially produced aluminum extrusions with a wall thickness of 0.6 mm. The aluminum extrusions have the form of a comb with three conductive walls in each cell; the fourth side is left open for the cathode strips.

The aluminum extrusion assembly is inserted into a long plastic sleeve which forms the gas volume. The ends of the sleeve are closed by caps which accurately position the anode wires and provide the necessary electrical and gas connections. Each endcap has a gas connector so a gas flow can be established down the length of the tube. One endcap has in addition electrical connectors for the high voltage and the eight anode signals. The high voltage is applied to the anode wires (unlike the MDT chambers) so the endcaps must be designed to take this into account. The common length of all the modules and the absence of severe restrictions on endcap size offer a significant simplification over designs used in the past.

Underground neutrino experiments have rather different requirements on the gas mixture than do collider experiments. The drift velocity and radiation damage requirements are relaxed significantly; the most important requirements are safety and reliability. We expect to use a standard, safe and cheap gas mixture such as Ar-CO_2 for our application.

The mode of operation depends on the detector design and the gas mixture. With the use of the aluminum combs as cathodes we prefer to use proportional mode. However the dependence of the detector performance (e.g. the resolution provided by the cathode strips) on high voltage and gas gain will be studied.

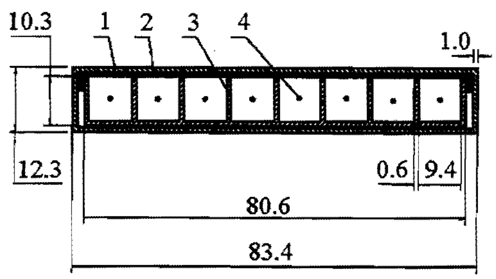

Figure 4.1: End view of an 8-cell module of minidrift tubes. The dimensions shown are in mm. The "cover" is not needed for our application.

The front-end electronics (8-channel amplifiers and discriminators) for the MDT chambers was developed as part of the D0 Muon Upgrade project [32]. We will consider the use of the same electronics for the anode-wire readout and possibly for the cathode-strip readout as well. Since the emulsion detector is to be included with the main MINOS detector data acquisition system we will be sure our electronics is compatible.

4.2 Construction of the Detector Modules

4.2.1 Description of a Basic Module

A 1 kiloton target employing emulsion technology requires that the target be assembled out of smaller more manageable units. An optimal internal structure for the emulsion modules is still under study. However for the following discussion we use a module design consisting of 50 Pb 1mm thick sheets interleaved with 50 double sided emulsion plates will be used. An emulsion plate is constructed out of an 800 micron thick polystyrene base coated on both sides with 100 microns of emulsion. Total module thickness is therefore 10cm. The transverse dimensions could range between 10cm $\times$ 10cm to 15cm $\times$ 15cm. A 1 kton emulsion target using the described module design would require up to 150 thousand modules and 8 million lead and emulsion sheets.

4.2.2 Module Assembly Requirements

4.2.2.1 Enviromental Requirements

The interleaving of the emulsion and lead plates must take place in the dark (red photographic lights are permissible) and under controlled temperature (70° F) and humidity

(65%). After completion of a module the unit must be wrapped in a light tight and evacuated container(or filled with nitrogen) and labeled with a unique identification number.

4.2.2.2 Treatment of Lead Sheets

Since the 1mm lead plates will be in contact with the active emulsion, precautions will be taken to eliminate chemical reactions between the lead and the surface of the emulsion. Tests done at ITEP[34] have shown that the combination of coating the surface of the emulsion sheets with a thin (~3 micron) layer of gelatin together with the thin oxide layer present on exposed lead sheets protects the surface of the emulsion from darkening up to 35 days. Additional tests with a planned duration of up to a year are in progress. Coating of the lead plates with acrylic paint or silver electroplating them are also being investigated to address the ESH issue of handling the large number of plates as well as to provide further protection for the emulsion surface.

An additional concern is the residual radioactivity in the lead. Experience has shown that lead smelted over 40 years ago has less radioactive contaminants when compared to modern lead[35]. It is imperative to determine what are these radioactive compounds and how they affect the emulsion. Tests will be conducted to identify lead sources which are of sufficiently low radioactivity to be implemented in the modules.

4.2.2.3 Labeling of Emulsion Sheets

The labeling of the large number of emulsion plates (7.7M plates/154K modules) required for the construction of the 1kton target is a daunting task. However the number of plates/modules that will actually be extracted and processed is a small fraction of the above number. Approximately 2000 neutrino interactions per 1kton×year are expected at the Soudan site. Therefore only ~8% of the plates will need to be permanently tagged [1].

After a module has been identified as containing a possible neutrino interaction, it will be extracted from the detector and disassembled in the dark. Each emulsion sheet will be permanently marked with a unique ID number identifying its parent module and the order of the emulsion sheet within the module. The marking will be a binary optical mark. A 38 bit binary word should be sufficient to uniquely identify each emulsion plate.

4.2.2.4 Alignment of Emulsion Sheets within a Module

The tolerances on the alignment of the emulsion sheets within a module are dictated by the requirement that we must link penetrating tracks from sheet to sheet within a reasonable time. The typical microscope field of view at the magnification needed is $100\mu \times 100\mu$ (see section on emulsion scanning). Therefore the alignment should be maintained to better than 20-30μ or 1 mil such that the position of the track projects to the subsequent plate well within a field of view.

A mechanical alignment of 10-20 mil is achievable with the schemes presented in Figures 4.2 and 4.3. Other scenarios to achieve better mechanical alignment are being investigated. In any regard, to obtain the final 1-2 mil alignment may require the use of straight through

[1] Assuming that only 1 module needs to be extracted and scanned for each interaction

going muons, either from cosmic rays or an accelerator. The scanning for this alignment process will be time consuming but will only be required once. It would involve scanning the individual emulsion sheets for the muon tracks, linking them between different sheets and thus defining the relative displacements between the emulsion sheets. To avoid confusion it is desirable that the charged track density is less then 10^4 tracks/cm^2 or < 1 track/field of view.

4.2.3 Large Scale Module Assembly Techniques

Due to the large number of modules required for a 1 kton target manual construction of modules is out of the question. The internal structure of the modules is simple and therefore an automated assembly line will be employed. Reuss Engineering in Warrendale, PA has been contacted and a preliminary design is being discussed.

The total number of modules(154K(69K)) need to be constructed over a 2 year period. Assuming 500 working days (machine downtime=30%), 300(135) modules/day need to be constructed. If the assembly line is supervised for 12 hours/day, a module construction rate of 25(12) modules/hr or one module every 2(5) minutes is required. To achieve this production rate a daily stock of 15000(7000) 1mm lead and emulsion sheets needs to be maintained.

A schematic of a possible robotic emulsion module assembly table is shown in Figure 4.4. Using the carousel scenario depicted in the figure and assuming we refilled the unit 4 times a day, we would need to reload 10 50 cm highlead and emulsion stacks (500 pieces/stack) every three hours(assuming one table). Each of the 50cm lead stacks will weigh ~45kg. To achieve the production rate described above it is envisioned that at least two of these units will be operating simultaneously.

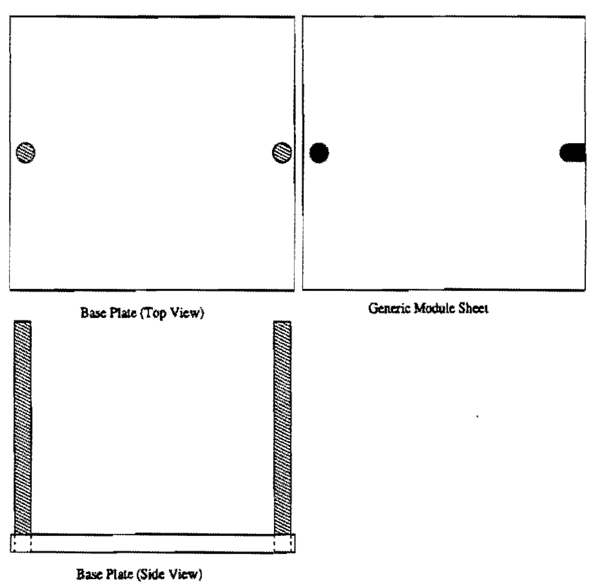

Figure 4.2: Possible scheme to achieve 10-20 mil alignment between emulsion plates within a module: Thread precision punched plates through precision rods attached to rigid base plates

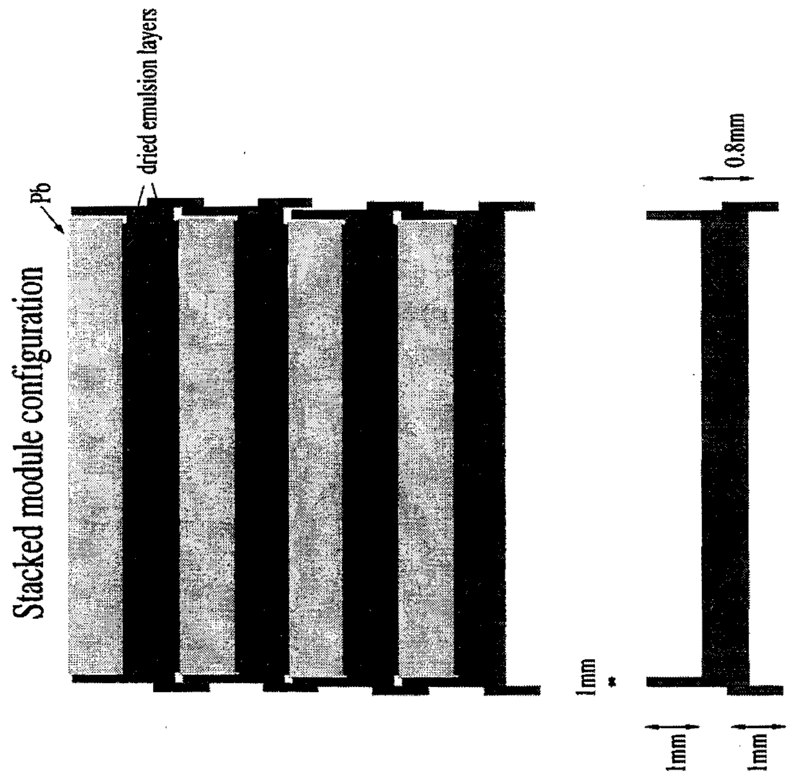

Figure 4.3: Possible scheme to achieve 10-20 mil alignment between emulsion plates within a module: "Lego" stacking of injection molded emulsion plates.

4.3 Support Structure

The MINOS Hybrid Emulsion Detector will be placed upstream of the main MINOS super-modules, and will require structural steel support for alternating vertical planes of emulsion modules and suitable electronic detector modules. The transverse dimension of the detector planes will be 5×5 m^2. For the purpose of our preliminary design considerations we assume emulsion modules $10 \times 10 \times 10$ cm^3 in size and 10 kg in weight. The design ideas presented here summarize work done by Norm Bosek of Bosek Engineering, Riverside, IL.

4.3.1 Detector Plane

The support structure for each emulsion plane is composed of 40 horizontal tubes laid on top of each other. Use of type 304 non-magnetic stainless steel is envisaged. A tube has a 12.5×12.5 cm square cross-section, with 0.3 cm thick walls, and a length of 500 cm or 250 cm. The corresponding design options would mean a single-tubelength plane, or two half-planes placed side-by-side. The latter option may be necessary to accommodate installation in a upstream section of the MINOS cavern and dictated by cost savings. Fig. 4.5 illustrates the arrangement for the single-tubelength option.

Ten tubes are skip welded together, transported by the mine elevator to the detector cavern where four of these subassemblies are joined to form a 500×500 cm plane or a $250 \times$

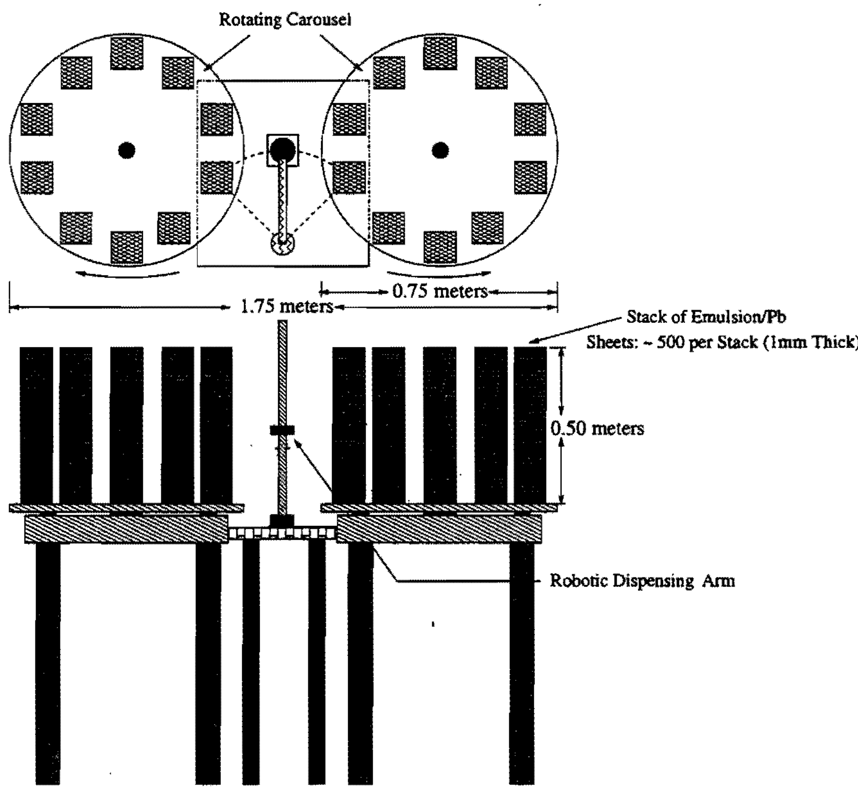

Figure 4.4: Schematic of robotic emulsion module assembly table.

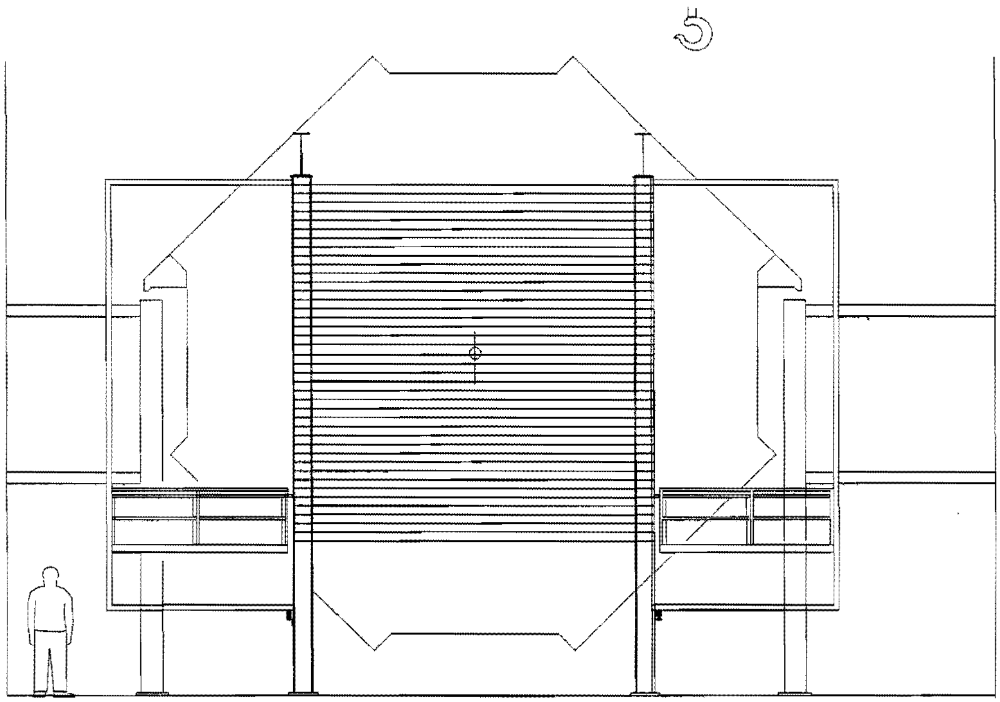

Figure 4.5: End view of the MINOS detector looking downstream, with the Emulsion Hybrid Detector standing in front of a MINOS Supermodule.

500 cm halfplane. How these subassemblies are to be joined together remains to be decided after advantages and disadvantages of bolting and welding are considered. Lifting eyes will have to be attached to each 10-tube subassembly since each weighs 300 kg and can only be moved by a crane. Rigging into the elevator cage and then out of the cage and through the tunnel into the cavern will have to be considered in detail. Obviously, the requirements for half-length tube assemblies will be much less stringent.

Details for mounting the electronic detector planes have not been specified yet. Obviously, there will have to be subassemblies that fit into the mine elevator, which will then be assembled into working detector planes (or half-planes) in the detector cavern.

4.3.2 Frame

Three concepts presently exist for mounting the 5-m-high vertical planes (or half-planes). The first one is to hang the planes from a steel structure composed of columns and an overhead beam, the second one is to have the detector standing on a low structure of short columns and horizontal crossbeams, and the third is to mine the cavern for the emulsion detector to a smaller vertical height making the floor level about 210 cm higher upstream of the MINOS supermodules so that the Emulsion Detector planes could sit right on the floor. So far, more attention has been paid to the first two alternatives.

Two designs, one with six columns and one with eight columns (Fig. 4.6) have been analyzed using the American Institute of Steel Construction (AISC) code. Optimal beams and

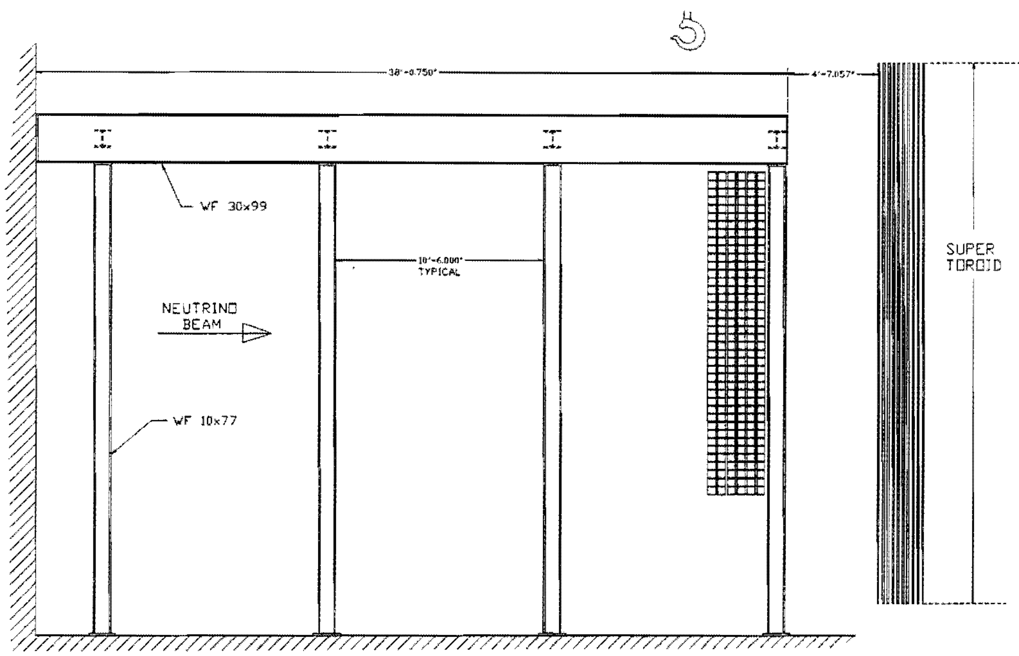

Figure 4.6: Side view of the MINOS Emulsion Hybrid Detector.

columns have been determined. Parallelograming of this structure in the upstream direction is prevented by overhead beams running to the cavern upstream wall. Parallelograming downstream is still in question because it is not known what pullout load the upstream cavern wall can withstand. Diagonal tension rods in each column bay on the east and west side of the structure would prevent parallelograming, but this would interfere with some module drawer removal as well as with electronic plane installation.

Either design for supporting the detector from underneath would still require a method to prevent parallelograming. In the case of half-plane design of the detector, a vertical steel plate 5 m high, 10 m long and 0.5" thick could run down the centerline of the detector, and could be used to prevent parallelograming.

4.3.3 Drawer

Every tube in the Emulsion Detector (half)plane contains a drawer in which the emulsion modules are placed. In our preliminary design, a drawer is a long narrow chassis that holds 21 emulsion modules side by side Fig. 4.7. A drawer is 250 cm long, so there is a right-hand and a left-hand drawer whether the tube is full length (500 cm) or half length (250 cm). The drawer's function is to allow easy access to any of the emulsion modules, no matter how deep in the detector is their location during data taking.

The drawer will have a front panel with a handle to aid in extracting it from its tube, and an inside end lip to constrain the emulsion modules. The drawer will be made of metal (to be specified) and its bottom will glide on the inside surface of a horizontal tube. Since a loaded drawer will weigh 190 kg, friction for sliding the drawer is a major consideration.

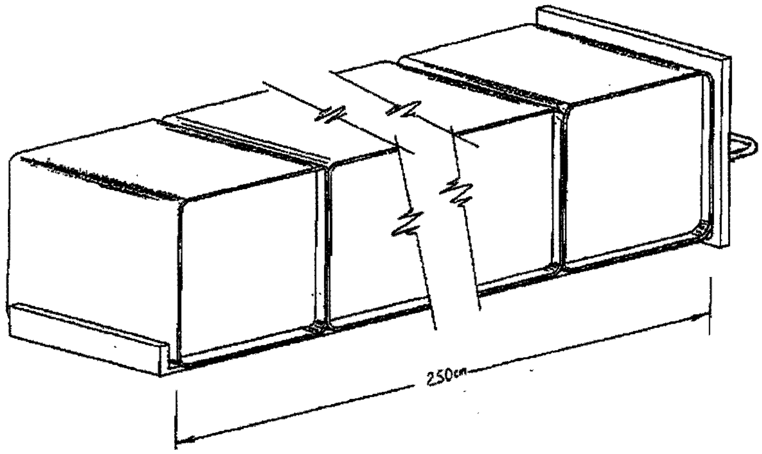

Figure 4.7: A drawer to hold 21 emulsion modules in a detector plane.

DU bearing material, lithium grease, or needle rollers on the bottom of the drawer will have to be investigated so as to limit the coefficient of friction to about 0.05 so that the pull-out force will be about 100 newtons.

A fastener may be needed on the drawer's front panel to lock it into the tube end, to ensure that the assembly remains in a known position in the detector plane.

4.3.4 Module Service Platform.

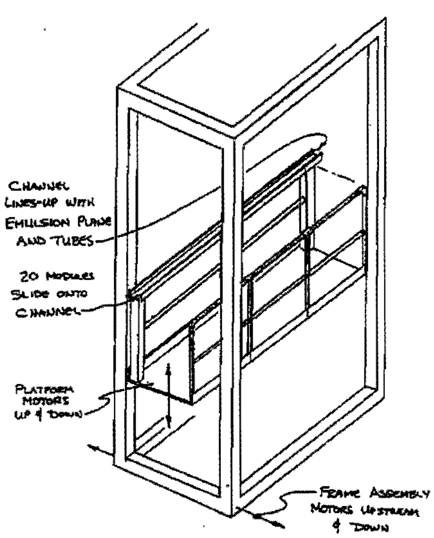

Figure 4.8: A module service platform, one required for each side of the detector.

To make possible a regular removal and replacement of emulsion modules within the detector, a service platform depicted in Fig. 4.8 will be built for each side of the detector. This platform will be motorized in both the up/down direction and along the beam (z). The outer framework will move in z by motor, and could be indexed electrically to automatically line up with each plane of tubes. Within the frame, a personal platform will move vertically by motor and also could be indexed electrically to line up with any tube in one plane.

A handrail will form one side of the platform. The other side will have a 15 cm wide steel channel as its top handrail running the length of the platform. When this channel is lined up with the bottom edge of a tube, the module drawer can be withdrawn from that tube onto the channel to access any module needed.

A track running on the floor will guide the entire platform assembly. The motors for both directions will drive either power screws, or a hydraulic oil pump/cylinder system. Motorcycle chains, sprockets and shafts will move each corner of the platform and the inside and outside edge of the frame. By the use of sprockets and shafts, the edges are moved in unison and parallelograming is prevented.

Most of the platform assembly will be welded together and built outside of the mine. There will, however, be some bolted joints to allow disassembly to a size appropriate to allow transportation down the mine shaft.

4.4 Infrastructure, Installation and Integration

In this section, we discuss plans for the installation of the detector, retrieval of modules for processing, integration of the emulsion detector with the MINOS supermodules and supporting infrastructure at Soudan.

4.4.1 Infrastructure at Soudan

The installation of an emulsion detector will require the development of some infrastructure at Soudan to support the manufacture of the detector components, construction of the detector, and processing of retrieved modules.

For the purposes of this proposal, we assume that the emulsion sheets may be poured, dried and assembled into detector modules entirely above ground. It might also be desirable to develop the emulsion above ground in order to use the cosmic rays as alignment markers within a module. The question of the radiation background due to cosmic rays, its effect on the readability of the emulsions and its impact on the required scanning time is still being studied. It may be that some or all of the work with emulsions might be better performed below ground, but this is liable to be more difficult logistically and more expensive.

The MINOS Project includes plans for a surface storage building to provide office, storage and shop space during installation, operation and decommissioning of the MINOS detectors[2]. This building is presently planned to be sited at the old Soudan School in the village of Soudan. An addition to this building could be constructed as an emulsion module factory. We discuss here a factory capable of producing 325 modules per day, each containing 50 one-sided emulsion sheets. This factory would require approximately 1800 sq. ft. of floorspace. A preliminary floorplan is shown in Fig. 4.9. The size requirements are driven by the space

[2] University of Minnesota, CNA Consulting Engineers, Ericksen-Ellison Associates, Inc., Miller-Dunwiddie, Inc., *MINOS Far Detector Laboratory Technical Design Report (including Basis of Estimate & WBS) for Cavern Construction, Cavern Outfitting & Detector Outfitting*, NuMI-L-263, October 1998

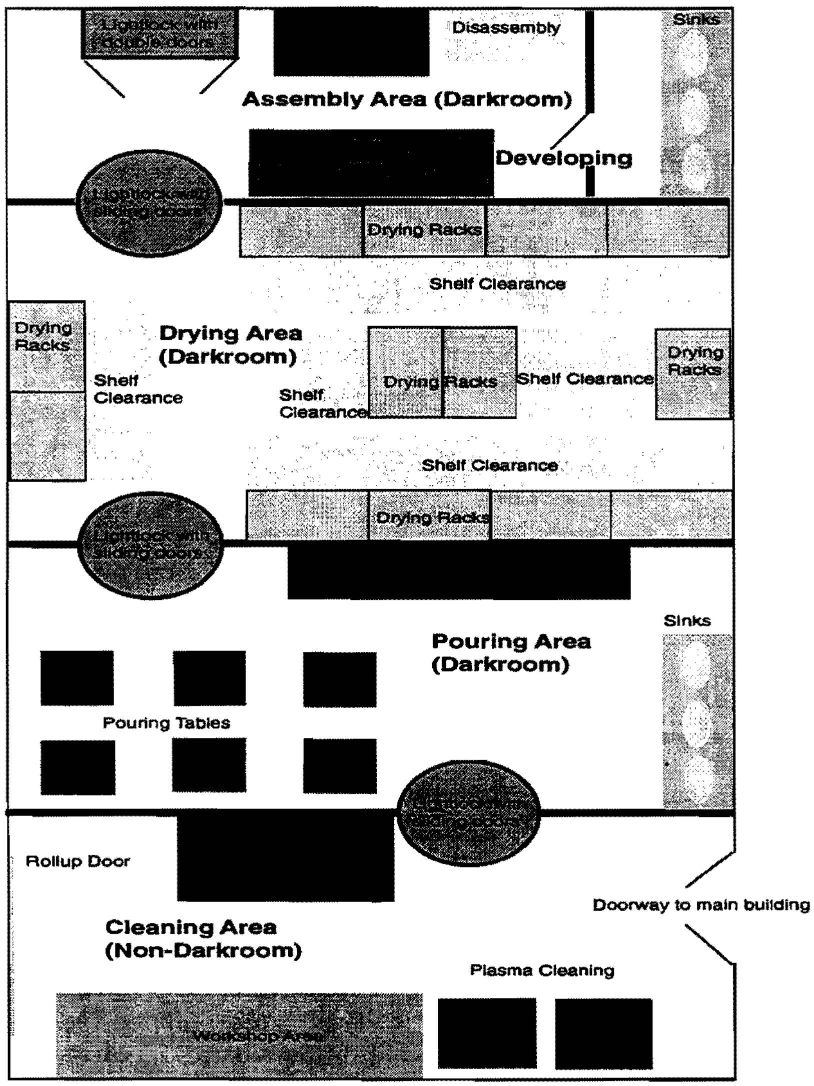

Figure 4.9: Floor plan of a possible emulsion modules production facility.

needed for drying the emulsion. The drying room as shown contains 13 racks. Each rack consists of 25 trays spaced vertically a few cm apart to allow adequate air flow for drying. In this design, each tray is 75 cm × 150 cm and accomodates 50 10 cm × 10 cm sheets, enough for a single module. Assuming a drying time of about 24 hours, this setup allows a throughput of 16,000 sheets (300 modules) per day. Note that if the sheets are to have emulsion on two sides, each would have to go through the drying process twice and hence the number of sheets (but not the total weight of emulsion) produced per day would be halved. Since 100 modules comprise approximately one ton of detector mass, such a factory could produce 3 tons per day, or 1300 tons in two 200-day years. This production would readily accomodate the construction of a 1 kT detector with ample capacity for the replacement of modules triggered during the construction period.

The factory would be divided into four main areas: an "open area" for cleaning and storage, and three darkroom areas for pouring, drying and assembly. The open area would contain storage areas for materials, tools and shop space as well as the equipment for plasma cleaning the plastic substrates for the emulsion sheets. In this area the plastic would be loaded into a standard sized tray, accommodating 50 sheets. The tray is grid-shaped, like a waffle iron, so that each sheet is supported only by its edges and is open on both sides. The sheets stay on one tray throughout the process of cleaning, pouring and drying up to the assembly stage. In this way handling of the sheets is minimized, reducing both workload and the possibility of damage. Two plasma cleaning machines which can accomodate 10 trays each will keep up with the capacity of the factory, assuming a 20 minute cleaning time and allowing 10 minutes to change out the trays.

The next stage is the pouring area. The trays of cleaned plastic are brought to pouring tables in the first darkroom area. If there are six (150cm × 150 cm) tables, each of which can accommodate two trays, then 27 pourings are needed to produce 325 modules. Allowing 30 minutes for each pouring leaves ample time to produce this amount in two shifts.

After pouring, the trays are brought to the drying racks in the second darkroom area. Here they are inserted as shelves into the racks and allowed to dry. If the sheets are to be two-sided, the trays are returned to the pouring room after the first side has dried, flipped over and emulsion is poured on the other side.

When both sides are dried, the trays are brought to the assembly area in the third darkroom area. Here the sheets are loaded into automated assembly devices.

4.4.2 Installation of the Detector

The first step in the installation of the detector will be to set up a framework to support a wall of modules and an associated layer of electronic detectors. Some discussion of this is given in the MINOS Detectors Technical Design Report.[3] The electronic detectors have yet to be determined, but the framework would have to allow for distribution of high voltage, readout and gas flow as needed. The framework will be such as to allow the modules to slide into it, as drawers. A movable platform, which can be raised to the level of the appropriate drawer of modules is used for access. The walls will be built one at a time, so that installation of the next framework may be ongoing while the modules are installed in the previous one.

[3]The MINOS Collaboration, *The MINOS Detectors Technical Design Report*, Chapter 11, October 1998

To install the daily output of 300 modules per day should be easily achievable. The total weight of 3 tons can be easily accommodated in a single elevator trip. The modules would be moved from the shaft to the detector construction area with pallet jacks. The time and labor to install the modules may be estimated as follows:

- 3 man-hours to load the modules onto a truck at the factory
- $\frac{1}{2}$ hour for transport
- 3 man-hours to load the elevator
- 3 man-hours to unload the elevator
- $3\frac{1}{2}$ man-hours to transport modules from elevator to framework
- 6 man-hours to insert the modules into the framework
- **Total: 19 man-hours**

Thus the module installation could be performed by three people in a single shift.

Since the emulsion is "turned on" immediately upon installation, it makes sense to have the electronic detectors for any given framework functioning before installation of the emulsion modules begins. The data acquisition phase begins with the installation of the first module. It is in fact likely that modules will be retrieved for development and replaced before the installation is complete. However, the module replacement demands (several hundred per year) during installation will not be so severe as to place a strain on the production facilities during installation.

4.4.3 Retrieval and Processing of Emulsions

On-line information from the electronic trigger counters will indicate the emulsion module(s) to be removed. As this occurs, a replacement module will be put in its place. The retrieval will simply be a repeat of the installation process of the module, since it will be replaced at the same time.

When the module(s) has been retrieved the next stage is to disassemble it and develop the emulsions. There are two options to be considered. On the one hand, the emulsion could be developed in the mine. This option all but eliminates the background from cosmic rays. On the other hand, if the emulsion were developed on the surface, not only are the logistics made easier, but cosmic rays could be used as fiducial markers for the alignment of the emulsion sheets. If one were to attempt this, however, it would be necessary to find a way to ensure that the plates do not slip relative to one another on the bumpy elevator ride to the surface. A possible solution that might allow this is to fill the metal cans containing the emulsion-lead sandwich assemblies with commercial packing foam. The sandwich assemblies would be wrapped in plastic to protect the emulsion from possible chemical reactions with the foam. Once the foam hardens, it would hopefully prevent any jostling of the alignment within the sandwich structure.

In either case, it will be necessary to mark the emulsion sheets upon disassembly. The marks are to provide spatial reference and to uniquely identify each sheet. In previous emulsion experiments with relatively few sheets wrapped in lightproof paper and foil envelopes, the challenge of uniquely identifying each sheet of emulsion was readily met with the application of a felt-tipped pen. For an experiment with 2,000,000 unwrapped sheets, this becomes less practical. Fiber optics offers a means of placing very small marks onto the emulsion sheets. Laser light directed through thin (100 micron or smaller) fibers can make very precise fiducial marks. A cluster of such fibers arranged in a rectangular array could provide a means of identifying each sheet, providing a time stamp of its removal, or other coded information. A switching mechanism integrated with the disassembly apparatus would light a pattern of fibers in the array. This pattern constitutes a binary number (light on/off) with as many bits as there are fibers in the array. The edge fibers might all be lighted simply to provide a reference grid. A 38-bit array with a reference grid could be placed in an area less than 1 mm square. This array may contain information indicating the position of the module within the detector, the position of the sheet within the module, and the electronic trigger which prompted its removal. This last datum will allow correlation of the event with the NuMI beam and with any corresponding muon track in the calorimeter.

After disassembly of the module, the lead plates will be recycled for use in new modules.

4.4.4 Integration With the MINOS Experiment

The integration of the emulsion detector with the MINOS calorimeter must take place in two phases. These are the installation phase and the operation phase. The systems integration goal during installation is to ensure that the efficient installation of the emulsion detector meshes smoothly with the installation and/or operation of the MINOS calorimeter. If one may make the following assumptions: that the installation of the emulsion detector will begin in 2001, that the installation of MINOS will remain on schedule, and that the construction and installation of the reference detector will take two years; then installation of the emulsion detector will span the installation of the first MINOS supermodule, commissioning of the first MINOS supermodule, and the installation of the second MINOS supermodule. This will require coordination of resources, including the use of the elevator, crane usage, manpower availability, and usage of space for storage of equipment and access to the far end of the cavern. The development of a detailed, overlapping installation schedule in conjunction with the calorimeter installation will minimize cost, effort and delays for both projects.

Operational integration with the MINOS experiment involves first the use of the NuMI beam. A GPS timing system is described in the MINOS Detectors Technical Design Report[4] and this same system would be used to obtain beam information for the emulsion detector. Secondly, the MINOS calorimeter can be used to identify, track and measure the momentum of muons produced by interactions in the emulsion detector. The electronic counters for the emulsion detector might be useful to some extent as a veto for the calorimeter, possibly adding a modest amount to the fiducial mass of the MINOS calorimeter. Finally, the downstream electronic detectors will need magnetic shielding from stray fields from the calorimeter.

[4] *Ibid.*, MINOS Collaboration, Section 6.4.6.

4.5 Data Analysis Issues

4.5.1 Overview

Tha analysis of data from the MINOS Hybrid Emulsion Detector(HED) will naturally proceed in two steps. The first step consists in utilizing the information from the HED electronic detectors and the MINOS main detector to identify the emulsion module (or modules) in which the neutrino interaction occurred and which may have information on the tracks near the interaction vertex. That information is then used to decide which modules should be extracted for processing. In addition, one wants to use this electronic information to further localize the position of the vertex and define the best strategy for the second stage of analysis, namely emulsion scanning.

The second step will consist of scanning the individual emulsion plates, starting with the most downstream one, and continuing upstream until the vertex is found. The goal of this latter phase is to identify events with possible kinks, i.e. tau production and decay candidates as well as electron showers and to obtain the maximum amount of information about them.

It would be premature at this time to attempt to define the final analysis system. This decision can only be made after a significant amount of additional information is available and it is the goal of the proposed R&D effort to obtain the input required. To design the ultimate system we need more information in such disparate areas as the nature of neutrino interactions and evolution of the resulting secondaries, detailed performance of the HED tracking system, the nature of the emulsion used and the specific geometry of the emulsion planes.

In light of the above we shall limit ourselves here to a rather general discussion of the main scanning issues. We shall also give a brief description of the scanning and measuring systems currently in operation in some of the MINOS institutions. The primary function of these systems is to serve as tools to provide feedback in our program to develop optimized emulsion for the MINOS experiment. But they will also provide a useful prototype that is a necessary first step in the design of the ultimate system.

Definition of the optimum scanning system requires an appropriate compromise between quality of localization from the electronic system and the minimization of scanning time. Very likely the advances in computing technology which can be anticipated in the next 4-5 years will have a strong influence on this optimization.

The majority of the observed neutrino interactions will be either ν_μ CC events or neutrino NC events. The diversity of tau decay modes implies that all of these will need to be investigated as possible tau candidates. Within each one of these two categories the events can be further categorized as either shower or non shower events, depending on whether at the electronic detector plane there are significant electromagnetic components due to primary or secondary pi zero's or electrons. The strategy that one would adopt in devising an optimum scanning algorithm would most likely be quite different for those four categories. Non-shower CC events should be relatively straightforward to track back to the vertex; shower NC events would lie at the other end of the spectrum.

The basic module is envisaged as roughly 10cm long (in the beam direction) corresponding to an amount of lead of about 10 r.l.'s. This means that the majority of electromagnetic showers will be at their maximum at the electronic plane conceivably allowing only rather poor localization of the transverse position of the vertex. Thus one anticipates having to do volume scanning for the majority of these events. On the other hand non-shower events may allow rather precise localization of the few tracks present at the electronic detector plane and tracking them back to the vertex would be rather straightforward. CC events will contain a muon generally well measured in the HED and MINOS scintillator system. This would allow for fairly precise prediction of the position and angle of the muon track at the emulsion plates except for those events where a large shower would not permit tracking the muon all the way back, thus degrading the position and direction information because of the Coulomb scattering.

4.5.2 Microscopic scanning of nuclear emulsion

We now turn to a discussion of the mechanics of microscope scanning of nuclear emulsion. The traditional method of using optical light microscopes with an objective and condensor, augmented by CCD readout, appears to be the most feasible mechanism for extracting the location of grains. A typical oil-immersion objective designed for biological purposes can offer fields of view in the range of a few hundred microns, and depths of focus in the range of 3-7 microns. A typical developed silver grain is less than 1 micron in diameter.

Position resolution in X and Y is determined by the CCD image resolution. A CCD image typically has 640x480 resolution, which can cover a 100 micron x 100 micron area in the field of view of a typical objective. Thus, we can expect the resolution of grain position in the X-Y plane to be roughly 0.2 microns.

The volume of nuclear emulsion data is likely to be dominated by the NC-like events. CC-like events will tend to produce relatively little data, because the muon track reconstruction will give a relatively accurate position prediction (*few mm*) in addition to the angle of the muon track, thus greatly reducing the scanning phase space. As mentioned previously, in NC-like events there is no muon track. For the purposes of subsequent discussion, we take a pessimistic view that for each NC-like event only a rough position ($\approx$ 1 *cm*) for the event will be available from the trigger information. It is then likely that a large volume of micro ($\approx$ 1 cm^3) will have to be scanned for each NC-like trigger, in addition to searching through a large volume of phase space for tracks. The stages for reducing data are shown in table 4.1, along with the amount of micro-emulsion data associated with the trigger for a worst case NC-like event. In this Table we have assumed a volume scanned region of 5 cubic centimeters in the emulsion detector for a triggered event, 640x480 CCD pixels, 3 grains per $10 \times 10 \times 10$ μm^3 of emulsion, an average of 1 track segment per $100 \times 100 \times 100$ μm^3 of emulsion, and roughly 100 tracks in the scanned volume.

Since we expect $\approx$ 2 NC-like events per day in a 1 kiloton detector, it should be possible to save all of the grain information to mass storage, and all of the track segments to hard disk. The reason for the low event rate is due to the very long neutrino beamline and consequent dilution of the neutrino flux. Previous accelerator searches for tau neutrinos with nuclear emulsion were located relatively close to the source and thus had much higher neutrino event rates.

In MINOS, because of our low event rate we should be able to perform sophisticated track reconstruction algorithms. For example, track distortions due to emulsion instability can be

stage of data reduction	amount of data per trigger (NC-like only)
analog CCD signal	
digitized CCD signal	$\approx$ terabyte
grains	$\approx$ gigabyte
track segments	$\approx$ megabyte
tracks	$\approx$ kilobyte

Table 4.1: Emulsion detector data reduction

analyzed in detail. Similarly, algorithms for identifying non-linear tracks from Compton scattered electrons due to radioactive emission of gamma rays in the emulsion and lead can be studied.

We have now some initial information about scanning speeds based upon micro-emulsion scanning systems setup in parallel at Stanford University and Fermilab, outlined in Figure 4.10. Standard Leitz-Ergolux optical microscopes with 10 $cm \times 10$ cm motorized stages were instrumented with CCD cameras and stepper motor drivers. Pentium desktop computers were outfitted with National Instruments frame-grabbing and motor controller cards. The control and analysis software was LabWindows/LabView.

The emulsion sheet was mounted on the stage and the X-Y-Z stepper motors automatically raster scanned the entire volume of several square millimeters of 100 micron thick emulsion. Grain extraction was performed at a rate of roughly 10 seconds per $100 \times 100 \times 100$ μm^3 volume of micro-emulsion. Grain data was stored on disk, and offline processes reconstructed track candidates from cosmic rays and/or test beam particles. The factors which determined the achievable speeds for grain extraction were mechanical stepper motor coupling and CPU. An analysis rate approaching a fraction of a second per $100 \times 100 \times 100$ μm^3 volume of micro-emulsion should be achieveable with a more optimally designed stage-motor system, and better optimized grain extraction algorithms/hardware. With a final design goal corresponding to one day per NC-like event, we should be able to scan all the triggered events in real-time with a farm of several dedicated microscopes.

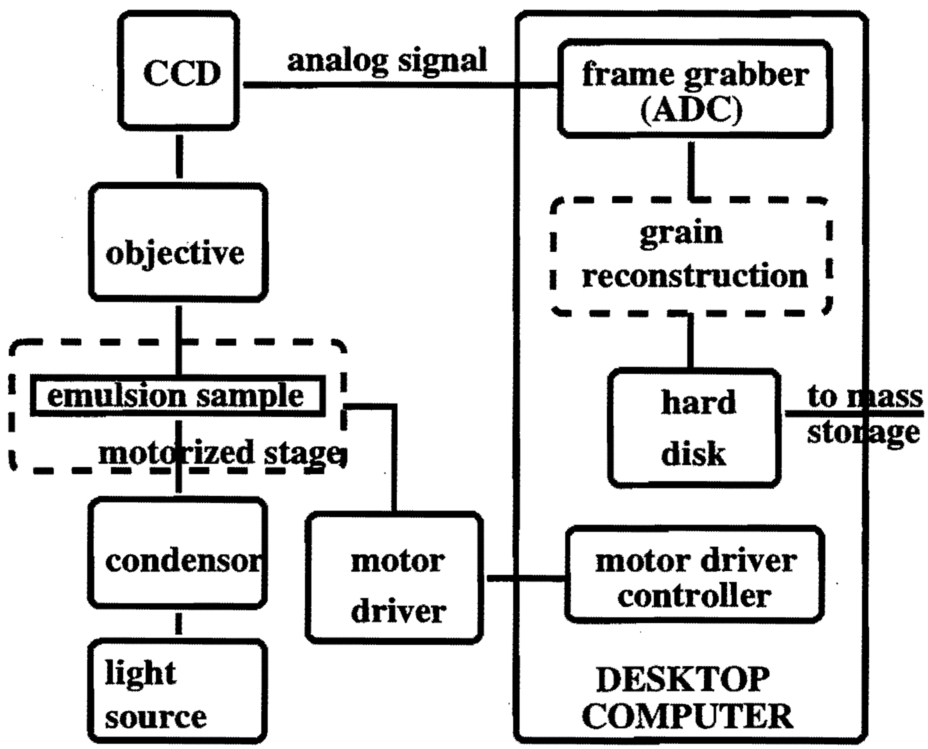

Figure 4.10: Emulsion optical microscope readout scheme.

Chapter 5

R&D Program

5.1 Overview

There have been many successful emulsion experiments, which have established credibility of this detection technique. The latest round of experiments: JACEE[36], CHORUS[21] and DONUT[19], have demonstrated the practical applications of all of the principal aspects of the detection technique necessary for the long baseline neutrino oscillation experiment: production of emulsion plates, emulsion/lead sandwich, automated scanning and analysis stations. The question, therefore, arises: what remains to be demonstrated before a realistic proposal for the experiment can be submitted? To answer this question one must explore the differences between the past experiments and the proposed one.

There are several chief differences:

- the overall dimensions of the detector, hence the total volume of the emulsion plates required. The biggest experiments to date have instrumented volumes of the order of one m^3; the proposed experiment will require some $250m^3$ of active volume.
- energies of the detected interactions and secondary particles. Multi-TeV interactions were studied with JACEE. Several tens of GeV neutrino interactions were detected in CHORUS and DONUT. A long baseline oscillation experiment requires neutrino energies around $10GeV$, especially if Δm^2 is small below $5 - 6 \times 10^{-3}eV^2$).
- previous experiments were carried out in the presence of major backgrounds from throughgoing muons or cosmic ray interactions. An underground experiment will be practically background-free.
- previous experiments had a large number of interactions accumulated in a relatively small volume of the detector. In our case we expect a small number of interactions distributed over a very large volume. This implies that the optimal analysis method may be quite different.

The proposed experiment will require emulsion plates with a total area of $80,000m^2$ and, assuming two 100μ thick emulsion layers, will contain $16m^3$ of emulsion. This unprecedented volume of emulsion leads to the following questions:

- can such a volume of emulsion be produced?
- the cost of such a volume of emulsion, at current prices, would exceed $100 million. What are possible cost reduction factors due to possible large scale production techniques or/and a possible optimization of the emulsion?
- how can one produce the required area of the emulsion plates? Traditional, manpower intensive methods are clearly not applicable at this scale.
- what are practical construction methods for a very large number of detector elements? What are the limits of the achievable construction precision and alignment?
- what are the trade-offs between the expected analysis load and the possible precision (and cost) of the electronic tracking detectors? What are the limits of track localization related to shower development in realistic detectors ?

The relatively low energy of the NuMI neutrino beam will result in low energy $\tau's$ to be detected. The τ lifetime corresponds to a $89\mu m \times \gamma_{Lorentz}$ decay path, hence we must be able to detect the τ and measure its direction over a very short distance, of the order of $100 - 200\mu m$ .This requirement leads to the following questions:

- what is the optimal geometrical configuration of the emulsion detector to ensure adequate detection efficiency and angular resolution?
- are the systematic errors due to distortions introduced during mass production of the emulsion plates small enough that they do not create significant background?
- what are possible methods for calibration of the distortions of the emulsion during the fabrication, processing and analysis stages?

5.2 Emulsion R&D

5.2.1 Emulsion Optimization

Nuclear emulsions sensitive to minimum ionizing particles have been pioneered by Ilford in the late 40's. Later they were produced by Kodak and NIIKFI (Moscow). Most of the recent experiments have used ET7B emulsion gel produced by Fuji. Demand for the emulsion is rather small and unpredictable; as a result there is no commercially available product. Small quantities are produced for specific experiments, in small production facilities.

We have established contacts with all potential suppliers of the emulsion gel: Fomos (former NIIKFI), Fuji, Ilford and Kodak ,and we plan to initiate some collaborative efforts to identify possibilities to produce the required amount of the emulsion gel at an affordable cost. The low background environment of an underground mine should enable an unambiguous and efficient detection of particles with as few as 20 grains per $100\mu m$ of track. The principal cost-reducing factors we hope to investigate are the following:

- utilization of large volume production facilities, rather than small R&D setups

- better sensitization techniques of the emulsion gel. Several samples of highly sensitive emulsions with grain densities approaching 70 grains per $100\mu m$ of track have been produced in the past.

- dilution of the emulsion with gelatin. This technique, leading to slower than naively expected reduction of grain density, has been initially investigated at Ilford[37]. Recent studies conducted at Nagoya[38] indicate that this method remains a very attractive cost-saving technique, especially if highly sensitive emulsion can be used.

Despite the lack of commercial applications, details of the emulsion production process remain a tightly guarded secret. Therefore the first two factors will be investigated by the emulsion vendors, with our participation limited to the evaluation of the quality of various emulsion samples. We plan to construct small emulsion detectors using provided samples of the emulsion, expose them to minimum ionizing particles and evaluate the sensitivity, latent image lifetime and long term stability of the sensitivity. This evaluation should help the vendors in optimizing the parameters of the production process

We plan to experiment with diluting and subsequent processing of emulsion to establish possible cost reduction factors. It is likely that dilution of the emulsion for the final experiment will be incorporated into the production process at the vendor's site.

A large volume of emulsion to be processed into plates requires efficient quality control procedures. Sensitivity of the emulsion batches must be controlled on a regular basis to avoid waste of materials and manpower. We plan to investigate several methods of semi-automatic evaluation of emulsion quality using radioactive β sources, following ideas developed at ITEP[39].

5.2.2 Latent image lifetime optimization

Optimization of the emulsion may rely on the very low background environment of the underground mine. To keep this background at the desired level it may be necessary to produce and process the emulsion plates underground. We are seriously considering such a possibility.

On the other hand, it is very important to explore the possibility of producing the emulsion plates above ground, perhaps even at the vendor's site, without creation of unwanted background. We plan to explore at least two methods:

- design emulsion with finite and controlled latent image lifetime. Initial discussions with FOMOS[40]experts indicate a possibility that an emulsion with latent image lifetime of the order of one month can be produced. With such emulsion, plates could be produced at the most convenient location and, after a month or so in the underground detector, would be restored to their low background state. Such an emulsion would have an additional advantage that even the inevitable background due to the mine environment observed in a developed emulsion would only correspond to the short period before the emulsion was processed.

- underground refreshing of the emulsion plates produced elsewhere. We are planning to evaluate various methods of erasing the latent image present in the emulsion and their influence on the long term properties of the emulsion.

5.2.3 Production of emulsion plates

5.2.3.1 Plastic base

The plastic base for the emulsion plates must meet high standards with respect to its physical and chemical properties. The most important of them include:

- high optical transparency (must not be bi-refringent)
- dimensional stability
- antistatic properties
- no curling
- good wettability (hydrophilic)
- good adhesion of the gelatin-based emulsion
- chemical inertness

Several types of suitable plastics have been identified by the photographic industry. The most common ones are:

- cellulose acetates
- polyesters
- polycarbonate
- polystyrene

An acrylic base was often used in particle physics experiments.

Some of the popular plastic bases are not suitable for our applications (polyesters tend to be bi-refringent, polycarbonates exhibit poor dimensional stability). We plan to evaluate several possible candidates, taking into account their suitability from the photographic point of view as well as the overall manufacturability of the detector.

5.2.3.2 Plate Production

Construction of 8 million plates can be achieved by pouring a smaller number of large plates and subsequently cutting them to the desired format. This latter needs to be done in darkroom conditions, and may require relatively tight tolerances.

We are planning to explore a technique of producing final-sized plates by injection molding of base plastic sheets. This technique offers very high reproducibility, high precision and high throughput at a very low cost. In addition it allows significant flexibility in the plate dimensions and shapes. In particular it offers a convenient method to produce the stackable plates as described in Chapter 4.

We plan to produce an injection molding form and produce a significant number of plates to evaluate this technique, as well as to experiment with construction of the detector modules.

5.2.3.3 Surface preparation of base plastics

Plastics are, in general, hydrophobic and exhibit poor adhesive properties. The surface of the plastic base must be rendered hydrophilic by physical (for example plasma treatment) or chemical (coating with appropriate agents) means. Adhesion of the gelatin-based emulsion can be improved by oxidizing processes, corona discharges or suitably selected plasma[41]. Anti-static coating is very important to prevent electrostatic discharges.

Properties of the plastic base are of critical importance for the experiment. It is essential to avoid delamination of the emulsion layer during the preparation of the detector, during exposure or during the photographic processing. We plan to investigate several methods of surface treatment and preparation to identify the most optimal method.

It is of equal importance to develop experimental methods for the measurements of the plastic surface and to assure its high quality before the actual coating with emulsion.

5.2.3.4 Coating plates with emulsion

Traditionally, the plates are produced by dispensing the required amount of gel and manuallly spreading it over the entire area of the plate. Although it should be much easier for the small plates of the proposed experiment, it is clearly impractical given the requirement of 8,000,000 plates. We plan to build prototypes of the automatic dispensing stations and waving/shaking tables to spread the emulsion. The dispensing system must provide good temperature control, to ensure proper flow of the emulsion gel. The waving table must include heating (for spreading) and cooling (for sol-gel transition) capabilities. The leveling of the table to better than $1mrad$ during the sol-gel transition is important to maintain uniform thickness of emulsion. Initial prototypes for production of single plates should establish principles for the second generation of facilities, capable of producing 100 plates at once.

5.2.3.5 Drying of coated emulsion plates

Some 90% of the volume of the liquid emulsion gel consists of water. The drying process consists of two stages: in the first, water evaporates from the solution as from the free water surface. In the second phase the evaporation rate is limited by diffusion of water through the layer of emulsion. It is very important that the humidity, temperature and air flow conditions are maintained very carefully during the drying process to reduce distortions. Distortions of concern for the experiment are related to stresses built into the emulsion layer during the drying process. These stresses relax during the wet stages of the photographic processing and cause displacements of the grains of silver.

We plan to construct a prototype of a drying cabinet to study the dynamics of the drying process and to establish optimal drying conditions for emulsion plates. Drying of an emulsion plate with a final thickness of $100\mu m$ takes some $24 - 36$ hours, and it is most likely to be the limiting factor in plate production.

5.2.3.6 Quality control

Given the volume, and the desired rate (some 15,000 emulsion plates per day) of expected plate production, it is imperative to develop fast and reliable quality control mechanisms.

We plan to construct an automated station for measurement of the plate thickness at all stages: before coating, after the first side and at the end. These measurements must be conducted in the dark and the contact with the surface of emulsion must be kept at an absolute minimum.

5.2.3.7 Industrial production of emulsion plates

If detector optimization studies should demonstrate that a thin ($\leq 50\mu m$) emulsion layer on a thin ($\leq 200\mu m$) plastic base is an acceptable configuration, then using more standard photographic curtain coating techniques of long films will be an attractive alternative to the batch processing described above. It will be particularly attractive if the background studies show that the background level inevitable in the emulsions produced above ground is in fact tolerable, or if a satisfactory emulsion refreshing technique is established.

5.2.4 Distortion studies

Tau identification will rely on detection of decay kinks of the order of $50mrad$. Angular measurement will be limited to thicknesses of the order of $100\mu m$, hence it is important that distortions in the emulsion must be kept down to a level of a micron or so, or that an adequate calibration procedure is available.

Distortions result from the emulsion displacement as a result of stresses induced in the fabrication process; therefore it is important to measure the distortions in the plates produced under realistic conditions.. We plan to construct prototypes of the double-sided emulsion plates using various emulsions under consideration and employing different plates and emulsion geometries (thicknesses). They will be exposed to high energy particles perpendicular to the plates. Silver grains adjacent to the plastic base, on opposite sides of the base, define the true track direction. Comparison of the position of the rest of the grains with the trajectory defined by the grains at the plastic interface will provide a direct measurement of the distortions. We will investigate the dependence of distortions on the details of the plate production process, position within the plate, thickness of the emulsion etc.

We will explore techniques of calibrating out the distortions. Loading emulsions with boron or lithium, and subsequent exposure to a thermal neutron flux[42] will provide samples of straight tracks of well defined length. Measurement of the actual length and shapes of these tracks may yield good estimates of the distortions.

During the fixing process a significant fraction of the volume of the emulsion is washed away. Subsequent collapse of the resulting voids may lead to displacement of the developed silver grains. This effect should be greatly reduced in diluted emulsions. In addition, we plan to explore methods for reduction of this effect by stiffening the gelatin structure via cross-linking.

5.2.5 Background Studies

We plan to take advantage of the presumed low level background in the underground environment.

It is important to know the level of this background, so that one could obtain a realistic estimate of the expected grain and track density in the developed emulsion. This is especially important since the background will be integrated over the entire lifetime of the experiment. This background will have several components: radioactivity of the walls in the mine and the mine air, radioactivity of materials in proximity to the emulsion (in particular the plastic base and the lead) and, finally the residual radioactivity of the emulsion itself. We plan to carry out an extensive set of background measurements in the Soudan 2 cavern to identify possible sources of backgrounds and to provide quantitative estimates of their magnitude.

In addition, we plan to compare backgrounds accumulated over a long time in the Soudan mine with those present in emulsion poured on the surface. This comparison will be used to decide what fraction of the production process needs to be carried out above the ground and which activities need to be moved underground.

We plan to determine backround to the tau samples due to particles scattering in lead, emulsion or plastic base using test beam exposures of detector prototype modules. In addition we will verify that particle momentum determination from the multiple scattering has adequate precision to enable removal of low momentum particles (below 1 GeV).

5.3 Engineering and Design

5.3.1 Robotic Assembly Techniques of Emulsion Modules

The proposed experiment requires some ~150K detector modules to be constructed. They need to be constructed in darkroom conditions, yet with relatively tight tolerances. We plan to construct a prototype of a robotic assembly station capable of stacking interleaved emulsion sheets and lead plates. We will use this station to produce a significant number of mechanical prototypes (using plain plastic, without the emulsion) to understand the complexity of the problem. We will also produce some modules using real emulsion to investigate possible effects of mechanical handling on the photographic properties of the emulsion and possible problems with static electricity discharges. These studies should lead to the optimized design of the production line: geometry of the assembly line, number of robotic arms, possible separation of lead handling and emulsion handling arms, optimization of the material storage and material flow, throughput etc..

5.3.2 Detector Support Structure

Real time analysis of recorded events is an important feature of the proposed experiment. We plan to construct a full scale prototype of one detector plane to verify engineering calculations and to verify experimentally the feasibility of the scheme for retrieving and replacing modules.

In addition we plan to continue the engineering studies of the proposed detector, to optimize the support scheme (hanging vs standing planes), to examine possible consequences of requiring a well-defined environment for the emulsion (in particular the possible requirement of cooling to 5^oC) and to explore the detector assembly methods, taking into account the MINOS cavern environment and the simultaneous construction of the MINOS detector.

5.4 Triggering and Event Localization Detectors (TELD)

These detectors must provide an event trigger, identify the module(s) where the interaction took place and localize particle trajectories to limit the effective area to be scanned in emulsion. The full detector will require some $2000m^2$ of these detectors, hence the technology must be an inexpensive one. Space limitation in the cavern impose additional constraints on the overall thickness of the detector plane. Trade-offs between the final emulsion analysis load and the resolution of the tracking detectors need to be investigated. We are currently investigating Iarocci tubes with cathode strip readout and planes of scintillator strips as possible technologies for these detectors. We also plan to explore possible improvements in the track localization capabilities by using X-ray film.

5.4.1 Iarocci Tube Technology

The main objective for Iarocci tube R&D is to optimize resolution, performance, and mechanical aspects of the design using D0 and DELPHI designs as a starting point.

Iarocci tubes used in counter mode will have 1 cm resolution and granularity. Resolution can be significantly improved if the tubes are used in drift mode. Resolution of 300-500 μm has been demonstrated with external triggering [31]. For the emulsion detector application we will study resolution in 'self-triggering' mode. The shower environment will probably necessitate multi-hit electronics. To investigate the effective spatial resolution in a realistic shower environment, we plan a test beam study of a realistic assembly of emulsion-like modules and Iarocci tubes.

Resolution of the cathode strip system can be optimized by adjusting the strip width. We plan to study optimal strip width through simulation studies and to build and test several prototypes of strip boards. Using the technique of weighting the induced charge on neighboring strips, a resolution of $< 1\ mm$ can be achieved with 1 cm wide strips. Since the number of channels directly depends on the strip width, optimization here is quite important.

The underground experimental conditions for neutrino detection impose rather different requirements on the gas mixture than those of other (e.g. collider) experiments. Requirements on the gas drift velocity, rates and radiation damage are relaxed significantly; instead the most important requirements are those of safety and reliability. We expect to use a standard, safe and cheap gas mixture for our application. Several standard gas mixtures (such as Ar-CO_2) are good candidates. We plan to study candidate gases and to optimize our choice from the point of view of the detector performance, cost and safety.

The mode of operation depends on the detector design and the gas mixture. We plan to use commercially available aluminum combs as the cathodes, hence proportional mode is preferable. We will investigate the dependence of detector performance on high voltage and gas gain.

Front-end electronics (amplifiers and discriminators) have been designed and developed by electronic engineers from JINR, Fermilab and Minsk (Belorussia) for the D0 Muon Upgrade project [32]. These will be the starting point for anode tube and cathode strip readout designs. The amplifier board must be redesigned to accommodate both wire and strip signals. The front end electronics should be designed to be compatible with the main MINOS detector DAQ for ease of integration.

5.4.2 R&D for Other Possible Solutions for TELD

We plan to study scintillation strip hodoscopes with wave-shifting fiber readout as an alternative technology. The R&D efforts would be directed at design optimizations that will allow either a decrease in the number of channels, or the reduction of the cost of each channel (making use of cheaper fibers, cheaper photodetectors and front-end electronics).

After preliminary studies of different TELD options we plan to build small size prototypes for preliminary testing of event localization in prototype emulsion modules, triggering, and front end electronics. If the detector is still feasible, a full scale prototype of the system should be constructed to test the mechanical and multi-channel electronics.

5.4.3 X-ray Film Sheet

One inexpensive way to improve the track localization would be to use x-ray film placed directly behind the emulsion module. It would provide high spatial resolution for tracks exiting the module while minimizing space and extramodule alignment issues. The x-ray film layer might be changed periodically, thus allowing for temporal discrimination of tracks.

We plan to investigate possible schemes of increasing the detection efficiency for minimum ionizing particles, for example by sandwiching x-ray films between intensifying screens. Such a technique has been successfully applied in cosmic ray studies to detect bare nuclei down to nitrogen (Z=7) [43]. This technique leaves a small spot on the x-ray film identifiable visually or with the help of a micro-densitometer. Expected localization resolution is of the order of $1mm$.

5.5 Scanning Techniques and Systems

We plan several tests of various emulsion configurations, and automatic analysis stations are indispensable as tools to analyze these tests.

The analysis load of the real experimental data is quite uncertain at the moment, as it depends on the achievable resolution of the electronic tracking systems, background environment in the mine and the number of events/plates to be scanned. Although it is very likely that the overall effort required will be of manageable proportions, we consider it important to start designing components of the final system. The analysis stations for the immediate tests will provide us with experience and a testing ground for the ideas and concepts of the final analysis.

5.5.1 Analysis station for emulsion tests

The scanning requirements for the emulsion detector can be categorized as near and long term. The near term goals are the establishment of scanning stations allowing us to perform diagnostic emulsion studies. The long term goal is the efficient and timely scanning of the neutrino interaction events accumulated from the data run with the 1 kton target. In this proposal we will concentrate on our short term scanning needs, however, with some foresighttThe emulsion scanning stations developed for the near term should be easily replicated and expanded to meet the future scanning load of the full data run.

In the near future we plan to expose and analyze several samples of emulsion plates with the aim of evaluation of the emulsion samples, background studies or evaluation of the detection efficiency and the effective angular resolution of different geometrical arrangements. These studies will require several automatic scanning stations with uniform measurement capabilities. At this stage the analysis speed is of no concern. We propose to establish four scanning systems at Fermilab, Pittsburgh, Stanford and Tufts to serve as primary tools for evaluation. We will install a uniform software environment and image analysis tools, to enable consistent analyses to be carried out. The emulsion analysis methods should be close enough to the final ones to permit conclusive measurements of the detection efficiency in the presence of noise, and of the effective angular resolution.

5.5.2 R&D towards the Final Scanning Station

5.5.2.1 CCD Camera Optimization

With typical objective magnification $\times 50$ and an inexpensive 1/3' CCD camera the effective field of view is of the order of $80\mu m \times 100\mu m$ and one pixel corresponds to $0.2\mu m \times 0.2\mu m$ in the emulsion. If the tracks can be predicted with $1cm^2$ precision, some 12,000 fields of view must be analyzed. Given that the developed grain size is of the order of $0.8\mu m$, it is probably better to try to enlarge the effective field of view to reduce the number of images to be analyzed. We plan to explore larger size CCD cameras as well as possible improvements of the videocoupler optics to optimize the scanning system for a maximal analysis throughput.

5.5.2.2 Grain/Pattern recognition Techniques

There are several methods used in the automated emulsion scanning techniques: from dedicated hardware track processors for a parallel analysis of a set of images, through customized programs running on general purpose computers to applications of digital image processing filters and morphology operations. Each of these techniques has its strong and weak sides, some of them produce complete tracks as an output, some of them result in the grain positions.

We plan to collect various algorithms and evaluate them for the particular application of a long baseline neutrino oscillation experiment. In particular, we plan to evaluate the robustness of different algorithms against different types of backgrounds, their detection efficiency, error rates and the overall timing.

5.6 Software

This section desribes plans to focus our effort on the optimization of the detector design and the evaluation of the physics capability of this apparatus.

5.6.1 Studies of Different Geometrical Configurations

The basic HED module will consist of alternating layers of lead and emulsion/plastic sheets. The simulation studies will attempt to determine what are the optimum thicknesses of the different layers. The answer will depend somewhat on the beam spectrum (which is another free parameter for MINOS) and, rather mildly, on oscillation parameters. An optimized detector would achieve an appropriate compromise between the total number of detected taus in a detector occupying the available space, the number of detected tau's per dollar spent, and the efficiency for tau detection. The performance will also be studied as a function of having either one relatively thick plastic layer double coated with emulsion or two thin plastic films double coated with emulsion and a thick plastic layer in between.

5.6.2 Electronic Detector Optimization

The track finding and scanning algorithms developed for experiments to date (e.g. CHORUS) are not appropriate for a long baseline experiment like MINOS. In our experiment one cannot afford to have electronic track localization immediately after each emulsion layer. Hence there will be some degradation of the kinematical information at the electronic detector plane due to nuclear scattering, Coulomb scattering, and development of electromagnetic showers in the (typically) 4.5 X_o of lead between the event vertex and electronic detector plane. The goal of the simulation program is to understand what event topologies look like and devise the optimum detector to obtain the relevant information. There are a number of specific questions one can pose here. Some of them are:

- How well can the muons be used to localize the vertex position? At what point does improvement in spatial resolution no longer help because of intrinsic Coulomb scattering?
- How much does 2D readout in one plane help as opposed to a 1D alternating projection readout in successive planes?
- How do scintillator and gas counters compare from the point of view of sensitivity to "noise", i.e. soft neutrons and low energy gamma rays? How important is this difference?
- How does the scanning time vary (for different categories of events) as a function of intrinsic spatial resolution of the non-emulsion detectors?
- What trigger is required to achieve close to 100% efficiency for triggering on tau events?

5.6.3 Physics performance

Simulations will be used to determine the detector physics capabilities (e.g. the efficiency for tau detection) and, very importantly, the potential backgrounds. So far very little work has been done on assessing our capability to detect tau decays in lead by the impact parameter method. These studies, performed as a function of lead thickness, will provide an important input to the determination of that parameter. The charm production rate will be simulated utilizing the best experimental and theoretical guidelines available and we shall study our capabilities to identify charm events, mainly through the presence of a primary muon in those events. The probability of scattering in plastic and lead will be simulated and compared with our planned test beam measurements. For the ν_e mode, we need to study the intrinsic limitations due to the ν_e background in the beam, the background from $\tau \to e$ decays, and the backgrounds from Dalitz π^0 decays as well as from gamma ray conversions very close to the vertex.

5.7 Required Resources

In this final section we summarize the resources required to accomplish our goal – formulation of a conceptual design for an HED by the end of FY00 together with a realistic cost estimate. We anticipate that this work will be carried out by the current MINOS collaborating institutions as well as by new groups (both in the US and abroad) interested in joining MINOS. Some of these new groups have interests that are very much focused on developing a hybrid emulsion detector for the MINOS experiment.

The funding requirements summarized in the following sections represent the total resources needed to complete our proposed R&D program during FY99 and FY00. Most of the total $1,479K will be requested directly from funding agencies, in the US and overseas, by MINOS collaborators. However, these collaborator funding requests must be legitimized by the establishment of a core R&D program at Fermilab, requiring M&S support of about $250K (included in the $1,479K). In addition, we request Fermilab support for two or three guest scientist positions during the FY99 and FY00. This endorsement of our R&D program by Fermilab will also provide the necessary organizational structure for the work, and will help to encourage new collaborators to join our effort.

5.7.1 Emulsion Optimization R&D

Item	Budget Request
Contacts and visits to emulsion vendors	$10K
Visits and consultation of experts	$20K
Emulsion gel and other materials, services	$35K
Injection molding mold and tooling, samples	$27K
Thickness measurement station	$15K
Dark room equipment (FNAL,Stanford,Pittsburgh)	$50K
Travel to test beam, Soudan	$20K
Test beam fixtures	$10K
Commercial emulsion samples	$10K
Automated pouring station equipment	$20K
Overhead 35%	$76K
TOTAL	$293K

5.7.2 Engineering and Design

Item	Budget Request
Robotic arm and controller	$31K
Engineering and design	$10K
Prototype module: materials and machining	$5K
Engineering of the detector structure	$50K
Prototype of full scale detector plane	$15K
Overhead	$33K
TOTAL	$144K

5.7.3 Triggering and Event Localization Detectors

Item	Budget Request
Iarocci prototype construction	$20K
Full-scale Iarocci prototype	$30K
Front-end electronics	$10K
Scintillator prototype construction	$30K
Test beam: travel	$10K
Test beam: fixtures and equipment	$10K
Overhead 35%	$39K
TOTAL	$149K

5.7.4 Scanning

Item	Requested Budget
Microscope frame (including z-axis motor)	$10K
Motorized stage 6"×6" (including encoders and controller)	$15K
Optics (objective, condensor, CCD camera, light)	$15K
Image processing (computer,frame grabber, software)	$15K
Overhead 35%	$19K
Subtotal (per system)	$74K
TOTAL (4 systems)	$296K

5.7.4.1 Manpower

Item	Requested Budget
4 post-docs @$50K	$200K
5 graduate students @$25K	$125K
0.5 programmer @$75K	$37K
2 FTE technicians @$45K	$90K
Overhead 35%	$145K
TOTAL	$597K

5.7.4.2 The Bottom Line

Item	Requested budget
Emulsion Studies and Optimization	$293K
Engineering and Design	$144K
Triggering and Tracking Detectors	$149K
Scanning Systems	$296K
Manpower	$597K
Grand Total	**$1,479K**

Bibliography

[1] F.Reines and C.L.Cowan, Phys.Rev.92,830(L),(1953)

[2] B.Pontecorvo, Zh.Eksp.Theor.Fiz.33,549(1957), ibid 34,247(1958)

[3] C. Athanassopoulos *et al.*, Phys.Rev.C55,2079(1997)

[4] R.Davis,Jr, D.S.Harmer and K.C.Hoffman, Phys.Rev.Lett.20,1205(1968), B.Cleveland *et al.*, Nucl.Phys.B38,47(1995)

[5] K.S.Hirata *et al.*, Phys.Rev.D44,2241(1991);
P.Anselmann *et al.*, Phys. Lett.B342,440(1995);
A.I.Abazov *et al.*, Phys.Rev.Lett.67,3332(1991).

[6] L.Wolfenstein, Phys.Rev.D17,2369(1978);
S.P.Mikheyev and A.Yu.Smirnov,Sov.J.Nucl.Phys.42,913(1985).

[7] R.Becker-Szendy *et al.*, Phys.Rev.D46,3720(1992)

[8] K.S.Hirata *et al.*, Phys.Lett.B280,146(1992).

[9] W.W.M.Allison *et al.*, Phys.Lett.B391,491(1997).

[10] Y.Fukuda *et al.*, Phys.Rev.Lett81,1562(1998).

[11] Y.Fukuda *et al.*, Phys.Lett.B335,237(1994).

[12] S.Hatakeyama *et al.*, Phys.Rev.Lett.81,2016(1998).

[13] Super-Kamiokande Collaboration, *Atmospheric neutrino results from Super-Kamiokande and Kamiokande - Evidence for neutrino oscillations*, talk presented by T.Kajita at the Neutrino 98 Conference, Takayama, Japan, June 1998.

[14] M.Ambrosio *et al.*, Phys.Rev.Lett.B434,451(1998).

[15] The MINOS Collaboration, *The MINOS Detectors Technical Design Report*, NuMI-L-337, October 1998.

[16] The Fermilab NuMI Group, *NuMI Facility Technical Design Report*, NuMI-346, October 1998.

[17] M.Apollonio *et al.*, Phys.Lett.B420,397(1998)

[18] E.H.S.Burhop *et al.*,Phys. Lett.65B,299(1976),
N.Ushida *et al.*, Phys.Rev.Lett.45,1049 and 1053(1980).

[19] T. Kafka *et al.*, Nucl. Phys. Proc. Supl.70,204(1999)

[20] N.Ushida *et al.*, Phys.Rev.Lett.57,2897(1986).

[21] E.Eskut *et al.*, Nucl.Inst. and Meth.A401,7(1997).

[22] S.A.Rabinowitz *et al.*,Phys.Rev.Lett.70,134(1993).

[23] H.Abramowicz *et al.*,Z.Phys.C15,19(1982).

[24] C.Baltay *et al.*,Phys.Rev.Lett.39,62(1977).

[25] B.C.Bosetti *et al.*,Phys.Rev.Lett.38,1248(1977).

[26] J.Blietschau *et al.*,Phys.Lett.60B,207(1976).

[27] See for example: P. Galison, *Image & logic*, p.193, The University of Chicago Press, 1997

[28] International Working Group for Photographic Gelatin (IAG), H. Ammann-Brass and J. Pouradier, *Photographic Gelatin*, Proceedinggs of the Fourth IAG Conference.

[29] Examples of important discoveries enabled by nuclear emulsions include: π and K mesons, Σ hyperon, hypernuclei.

[30] W. Busza *et al.*, *Experience with Iarocci tubes produced on a large scale* Nucl. Instr. Meth. **A265**, 210 (1988).

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

[32] G. Alexeev *et al.*, *Technical Design Report for the D0 muon detectors electronics*, D0 Note 2415,(1997).

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

[34] V. Smirnitski, ITEP, private information

[35] Y. Takahashi, University of Alabama, Huntsville, private information

[36] Burnett, T. H. *et al.*, NIM, **A251** , p.583, (1986).

[37] 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.

[38] Y. Kotaka, Nagoya University, talk at the I International Workshop on Nuclear Emulsion Techniques, Nagoya 1998.

[39] V. Shamanov, private information

[40] FOMOS, Moscow, private information

[41] J. Gregory, University of Alabama, Huntsville, private information

[42] Titterton, E. W., *Slow neutron Monitoring with Boron and Lithium-Loaded Nuclear Emulsion*, Nature **163**, p. 990 (1949).

[43] Ichimura, M. *et al.*, Phys. Rev., **D48**, p. 1949, (1993).