Chapter 10

Use of Soudan 2 in MINOS

10.1 Overview

It is the intention of the MINOS collaboration to use the fine-grained 1 kiloton Soudan 2 detector in conjunction with the new 5.4 kiloton MINOS far detector[1] to measure the properties of the neutrinos arriving at Soudan. The potential use of the Soudan 2 detector in a wide band beam from Fermilab has been described in considerable detail in previous documents which were submitted to Fermilab for proposal P-822[2]. At the present time, no upgrades or modifications of the existing detector are planned. The lower mass but finer granularity of the Soudan 2 honeycomb drift chamber complements the high mass magnetic 5.4 kt detector. In this Chapter there is a brief description of the Soudan 2 detector and an overview of the physics motivation for its continued operation.

10.2 The Soudan 2 detector

The design, construction, operation and performance of the Soudan 2 tracking calorimeter has been described in detail elsewhere[3, 4]. The central portion of the Soudan 2 detector is comprised of 224 rectangular modules each of dimension $2.7 \times 1 \times 1$ m^3. The detector is arranged in a $5 \times 8 \times 14$ m^3 array of modules. At roughly 4.5 tons per module, the total detector weight is 963 tons. Figure 10.1 shows a sketch of a Soudan 2 module.

Each Soudan 2 module contains a 241 layer stack of 1.6 millimeter thick corrugated steel plates. Between each layer of steel are sheets of Mylar ("bandolier") in which 14 mm diameter resistive plastic (Hytrel) tubes are inserted. The tubes are layed laterally, alternating between 31 or 32 per layer, and act as manifolds for a distribution of an argon and CO_2 gas mixture within the module. A plane of anode wires and cathode pads are mounted at each face of the array of Hytrel tubes. A section of a readout plane is shown in Figure 10.2.

As a charged particle penetrates a module, ionization occurs. The unbound electrons drift under the influence of high voltage copper electrode strips glued onto the bandolier. These electrodes vary in voltage (0 to 9000 volts) and are configured to force the electrons to drift up to 50 cm with a constant velocity (0.6 cm/μs) towards the readout plane of the module where the array of anode wires is held at a large positive potential (2300 volts). Figure 10.3 shows the drift tube and anode wire geometry and electric field configuration.

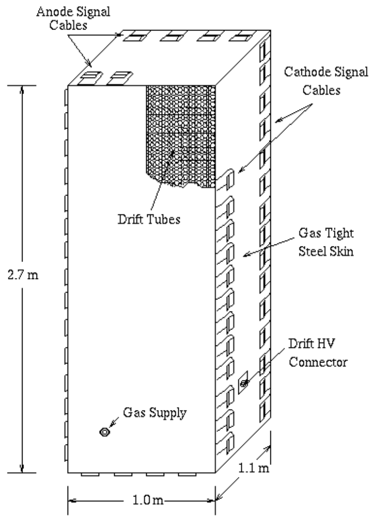

Figure 10.1: A single 4.5 ton Soudan 2 module.

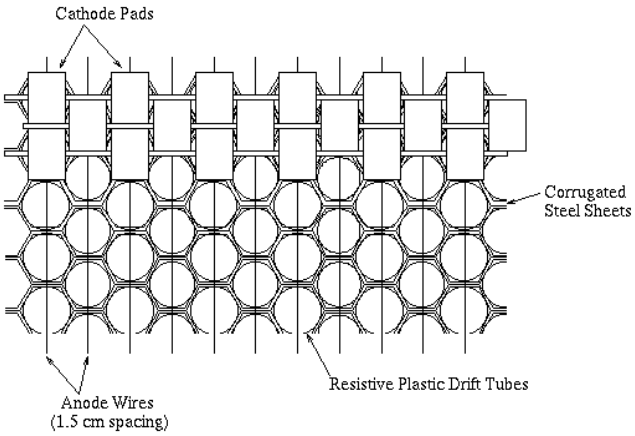

Figure 10.2: The readout-plane region of the detector, including the anode wires and three layers of the cathode pads.

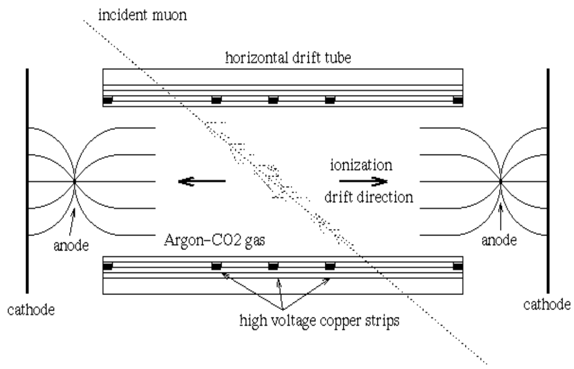

Figure 10.3: Cross section of a drift tube (not to scale).

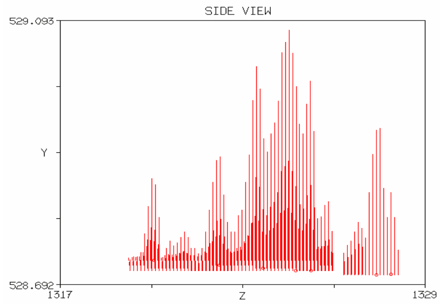

Figure 10.4: A Soudan 2 pulse on a cathode pad, showing several resolvable hits.

There are 63 anode wires and 240 cathode strips spanning both sides of each module. As the electron shower is collected onto the anode wire a mirror charge is induced on the adjacent horizontal cathode strip forming an electrical pulse. Each of these anode and cathode channels is connected to a signal preamplifier which is mounted directly on the module. The amplified signal feeds into a multiplexing ("summer") crate. There, the signals of up to eight channels are physically wired in parallel ("OR-ed"). The multiplexing scheme is done in such a way that hits can almost always be assigned to unique anode-cathode locations in the offline data analysis. The analog signal then is routed to the rack of Analog-to-Digital Converters (ADCs) which are monitored by a trigger logic circuit.

The orthogonal orientation of the anodes and cathodes forms two of the three orthogonal spatial dimensions that are recorded. The third dimension is calculated from the drift time and a determination of the initial time of the event, T0.

The currents on the anode wires and the cathode strips are sampled at 200 nsec intervals by flash ADCs. A raw pulse is defined as a contiguous sequence of measured voltages or micropulses which make up the pulse. Several cathode hits from such a pulse are shown in Figure 10.4. "Edges" occur when a particular ADC pulse is driven beyond a threshold voltage at a unique time. An event is triggered when a required cluster of eight anode edges or seven cathode edges is obtained.

The detector is surrounded ($\sim 99\%$ coverage) by a 1700 m^2 active shield mounted on the cavern walls. The shield elements are double layer aluminum proportional tubes. A double layer hit is recorded for 95% of the charged particles which cross a shield element. The calorimeter and active shield are shown in Figure 10.5.

10.3 Soudan 2 as a complement to the 5.4 kt detector

Although it would be too expensive to build an additional 5.4 kilotons of the Soudan 2 detector, there are many reasons to want to keep the existing detector running through the MINOS long-baseline experiment. These reasons are:

1. Cost effective additional mass
   Soudan 2 will contribute 15% of the total mass of the MINOS far detectors for much less than 15% of the cost. The only costs involved are some additional (small) operating expenses.

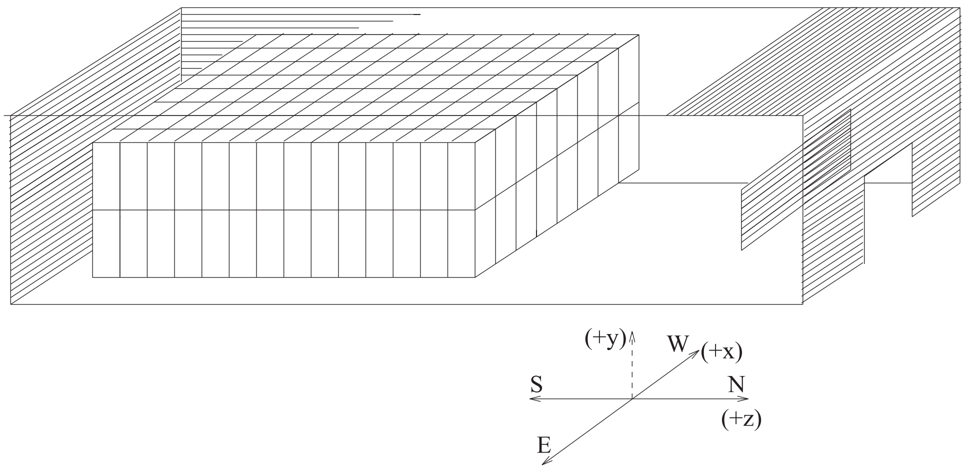

Figure 10.5: The relative orientation of the calorimeter (inner) and active shield (outer) for Soudan 2.

2. Readiness
The detector is ready now so it will be ready at the time when the beam turns on in 2002. There are no known detector aging issues which would prevent this.

3. Granularity
The steel thickness of 1.6 mm compares to the steel thickness of 25.4 mm in the 5.4 kt far detector. Due to the honeycomb nature of the detector, the amount of material between gas crossings is 8 times less than the 5.4 kt detector in the 0^o direction, and 16 times less in the 60^o direction. This finer granularity allows greater sampling of the ionization for a track or shower, which in turn can be a great aid in pattern recognition.

4. Area
The rates of ν interactions are proportional to mass, but the rate of measuring ν induced muons in the rock upstream of the detector is proportional to area. This muon rate, which is independent of rock density to first order, will provide a high statistics independent measurement of the rate of charged current events. Although Soudan 2 has 18% of the mass of the new detector, it is comparable in instrumented area, so it would provide a significant and independent measurement of the rock muons.

5. Low energy trigger threshold
The trigger threshold for the 5.4 kt detector will be a few GeV, and will not be known precisely until some of the detector is in place. It will fail to trigger on 10 to 30% of the neutral current events. Soudan 2 provides a detector with a very low energy trigger threshold. It is 50% efficient at 300 MeV kinetic energy and $>$ 98% efficient above a few GeV. This will provide a check of the trigger threshold in the new detector, as well as a measurement of the lowest energy neutral current and ν_e events.

6. Systematic errors
With Soudan 2, it will be possible to measure many of the properties of neutral and

charged current events in a completely independent detector. This will give an important systematic check on a number of the measurements in the new detector. Soudan 2 will be able to separate neutral current and charged current events based on both event length and tracking. For the lowest energy muons ($< 2\ GeV$) it will measure the range distribution. And for both the NC and CC events, it will measure the hadron energy distribution with better resolution.

10.4 Unique capabilities of Soudan 2

The excellent granularity of the Soudan 2 detector allows for certain measurements that are not possible in the 5.4 kt detector. The issues of recoil proton identification, low energy electrons, μ^+/μ^- separation and modularity are addressed in this Section.

In its exposure to atmospheric neutrinos, the Soudan 2 detector has shown that it is able to measure recoil protons[5]. About half of neutrino induced recoil protons are clearly visible in the Soudan 2 detector. These protons can be cleanly identified and separated from pions based on their ionization and straightness[6]. A full Monte Carlo described in the MINOS proposal reported that it would be possible to separate quasi-elastic $\nu_\tau p \rightarrow \tau n, \tau \rightarrow \mu\nu\nu$ events from ν_μ quasi-elastic events using the angle between the outgoing muon and proton in the plane transverse to the beam. Intranuclear scattering of the proton was not included in that simulation and somewhat weakens the ability to separate signal from background. However, for large mixing angles, this still provides a powerful and expected signal for τ identification. In general, measurement of the recoil proton aids in the angle and transverse momentum measurements for all of the events in which the proton is seen.

Low energy electron identification is another comparative advantage of the Soudan 2 calorimeter. The fine granularity of Soudan 2 couples with the fact that the radiation length of an electron from the vertex is very different from the interaction length of a pion. A ν_τ quasi-elastic event, followed by $\tau \rightarrow e\nu\nu$ decay, would produce a unique topology, in which an electromagnetic shower and a proton are identified, and transverse momentum is not balanced. The rates of high energy electron events in Soudan 2 would also be a valuable consistency check for the electron identification in the 5.4 kt detector.

Another advantage of the fine granularity is the ability to see μ^+ decay hits. In iron, μ^-'s are absorbed, while most μ^+'s decay at rest to make a positron. This allows for some μ^+/μ^- separation and will be a complementary measurement to the method of separation using the magnetic field in the new detector.

The modularity of the Soudan 2 detector allowed for a calibration using the ISIS test beam at the Rutherford Laboratory[7]. It also provides a great deal of flexibility for repairing module faults and for further calibration of any module in which an unusual event takes place. The modularity of Soudan 2 makes it possible and straightforward to assemble a near detector version of the Soudan 2 calorimeter should a clear motivation arise.

Chapter 10 References

[1] The MINOS Collaboration,"P-875: A Long-baseline Neutrino Oscillation Experiment at Fermilab," February 1995, Fermilab report NuMI-L-63.

[2] The P-822 Proposal is described in the following documents submitted by the P-822 Collaboration:
"Proposal for a long baseline neutrino oscillation experiment using the Soudan 2 neutrino detector," March 1991;
"Progress report and revised P-822 proposal for a long baseline neutrino oscillation experiment from Fermilab to Soudan," October 1993;
"Update to P-822: proposal for a long-baseline neutrino oscillation experiment from Fermilab to Soudan," March 1994;
"P-822 response to the PAC's questions of 11th April 1994," May 1994. There is also a further discussion of the measurement of quasi-elastic events on pages 168-172 of the MINOS proposal[1].

[3] W.W.M. Allison *et al.*, Nucl. Instr. Meth. **A376**, 36 (1996).

[4] W.W.M. Allison *et al.*, Nucl. Instr. Meth. **A381**, 385 (1996).

[5] W.W.M Allison *et al.*, Physics Letters, **B427**, 217 (1998).

[6] "Protonicity" by Peter Litchfield, March 1998, Internal note PDK-696.

[7] Proceedings of the First International Conference on Calorimetry in High Energy Physics, Ed. D.F. Anderson *et al.*, 1990, World Scientific (426). Also C. Garcia-Garcia, "El Experimento de Soudan 2 para el Estudio de la Establilidad de la Materia: Interacciones de Neutrinos," Ph.D. thesis, Universidad de Valencia, 1990.