

LONG-DRIFT CALORIMETER MODULES FOR THE SOUDAN 2  
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The first full size 5-ton detector modules for the Soudan 2 nucleon decay experiment have been assembled and operated. Modules consist of a hexagonal array of drift tubes and corrugated steel, instrumented to read out three-dimensional track positions and pulse height. These will be assembled to form an isotropic, continuously sensitive, self-triggering detector. Details of the design, construction, operation and performance of the modules are discussed.

Introduction

The Soudan 2 collaboration is preparing a second generation experiment to measure the nucleon lifetime.<sup>[1]</sup> Previous experiments have shown the importance of detailed measurements of the candidate events in order to reject neutrino background. The Soudan 2 detector was devised with special emphasis on the tracking of particles and measuring their ionization energy loss. Those goals are achieved by fine-grained  $dE/dx$  sampling, high spatial resolution, and three dimensional hit reconstruction. The result is a compact detector which records the details of event topology, allows particle identification, and determines track directionality. It is fine grained, highly isotropic, continuously sensitive, and self triggering. An artist's conception of the completed detector is shown in Fig. 1.

The main detector will be composed of 256 identical modules summing to a total mass of 1100 metric tons. The modular construction of the experiment allows the actual response to expected decay products and neutrino interactions to be measured with accelerator beams. The experiment is to

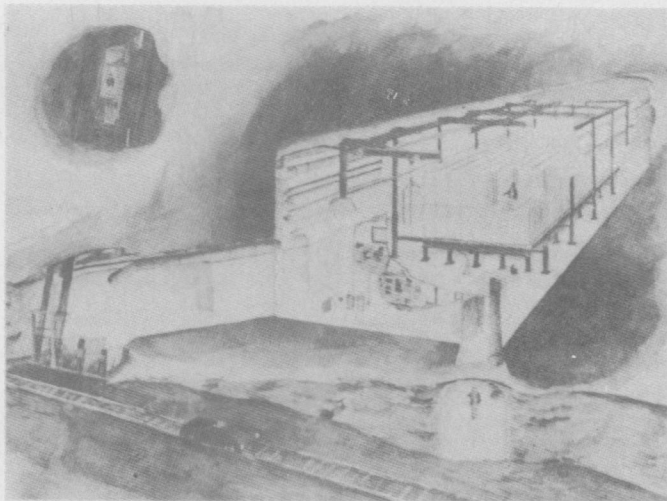


Fig. 1. Artist's sketch of the Soudan 2 Experiment. Preexisting mine work is shown in the foreground. The experiment counting house is at the near end of the cavity. The laboratory dimensions are  $14\text{ m} \times 12\text{ m} \times 72\text{ m}$ , which is large enough for an eventual 3300 ton detector. Excavation was completed in the Fall of 1985.

be installed in Minnesota's Soudan iron mine at a depth of 2200 meters of water equivalent, to shield the detector from cosmic rays. Further shielding is obtained by surrounding the detector with a two-layer proportional-tube active shield. The device is read out with custom electronics, implemented in Multibus and CAMAC. Control is via a VAX-11/750 which also does data recording. Online analysis of muon tracks is to be done using a 370E emulator with the VAX as its host.

The first two detector modules have recently been constructed at Argonne. This paper will discuss the details of their design, construction and operation. The basic features of the design are firm; however the experience of building modules has prompted improvements in many details and helped to optimize fabrication techniques for large-scale production.

Module Design

Soudan 2 detector modules employ long drift distances for ionization electrons in cylindrical gas volumes surrounded by steel. They make use of the extensive development in the last several years of

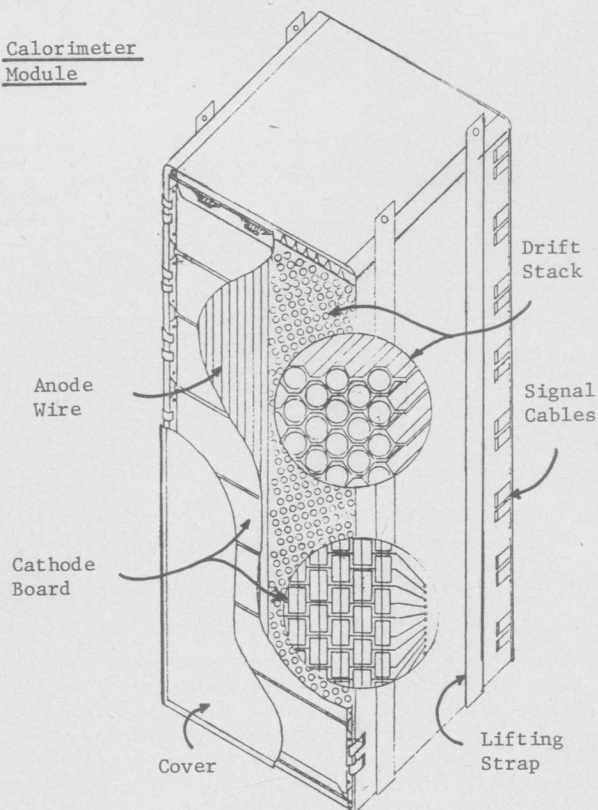
Calorimeter  
Module

Fig. 2. Schematic drawing of a calorimeter module. A module consists of a stack of corrugated steel sheets and plastic drift tubes as shown in the top detail. The bottom detail shows the multiwire proportional chamber.

calorimeters based on long drifting in tightly constrained geometries [2,3,4] to achieve an extremely detailed event readout with a modest number of electronics channels.

Figure 2 is a schematic diagram of a module, which consists of  $1\text{ m} \times 1\text{ m} \times 1.6\text{ mm}$  corrugated steel sheets, stacked 257 layers high to create an array of  $1\text{ m}$  long hexagonal holes. The 8064 holes are lined with  $16\text{ mm}$  diameter Hytrel [5] resistive plastic tubes captured within a laminate of  $125\text{ }\mu\text{m}$  Mylar. Copper conducting lines on the Mylar which run perpendicular to the tubes are charged such that a uniform axial drift electric field is established in each tube. Ionization electrons, produced by charged particles passing through an argon- $\text{CO}_2$  atmosphere in the tubes, drift in the  $200\text{ V/cm}$  axial field toward the closest end. The maximum drift distance is  $50\text{ cm}$ . Drifting electrons are detected by an orthogonal array of 63 proportional anode wires ( $50\text{ }\mu\text{m}$  gold-plated tungsten) and 256 cathode strips, located at either end of the steel honeycomb structure. The geometry of a single tube drift volume and anode wire is shown in Fig. 3. The entire assembly is enclosed in a gas-tight steel skin to complete a single module.

The assembly process is such that three major components must be put together. Corrugated steel sheets are prepared by thoroughly deburring and degreasing. The resistive tube and insulating Mylar assembly, known as "bandolier", has been made both in-house and by a commercial supplier. Figure 4 is an illustration of a section of bandolier. The multi-wire proportional chambers are also built in-house.

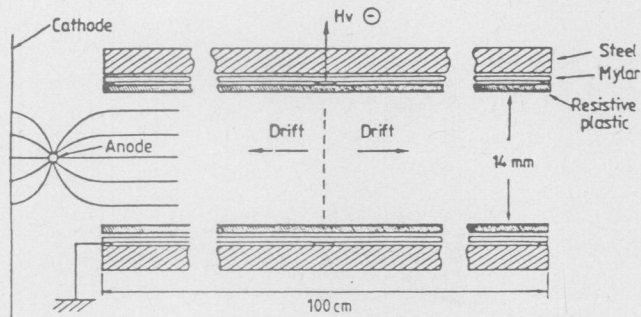


Fig. 3. Cutaway view of a single Hytrel tube with surrounding steel and Mylar insulation. The drift field is applied by a series of 21 copper strips between the tube and Mylar, of which only 3 are shown here.

Assembly begins with a load plate laid down on an assembly jig. Steel sheets are added one at a time while the bandolier is fanfolded in between and indexed to the corrugations. A major concern in stacking is maintenance of high precision in the positioning of the individual steel sheets and bandolier, because the face which they present to a readout chamber affects the relative gain and consequently the detector uniformity. When a stack is completed, a top load plate is added and the whole assembly is compressed to a pressure of  $10\text{ tons/m}^2$ . Compression improves tolerances in the vertical dimension and can partially compensate for the buildup of cumulative thickness errors. High voltage connections to the bandolier are made at this stage. The stack is tested

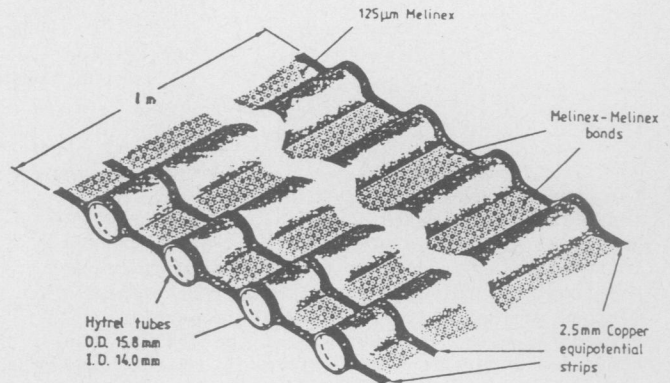


Fig. 4. Sketch of a bandolier assembly. The bandolier is made of Mylar (Melinex), copper equipotential strips, and Hytrel tubes. The copper traces are applied to the insulator in one production step. Then two of these sheets are bonded around the resistive tubes.

for high voltage integrity of the Mylar insulation in an argon atmosphere before the construction proceeds. Next the sides are welded on. Then completed readout planes are mounted and aligned to match the cathode pad pattern to the ends of the tubes, with particular attention to the flatness of the grounded cathode planes. Finally the module is sealed with steel covers. The 638 anode and cathode signals come out of the module on flexible flat cables which pass beneath the cover gaskets.

#### Operation

The operation of modules requires several support subsystems, including gas handling, high voltage, readout electronics, and a trigger. The detector operates in a gas mixture of 85% argon and 15%  $\text{CO}_2$ . Contamination by oxygen below the 5 ppm level is maintained by a purification-recirculation system. Other gases which affect drifting, especially water and electronegative contaminants, are carefully controlled. A short drift column containing an  $\text{Fe}^{55}$  source is used in-line with the system to independently prove the necessary electron lifetime is achieved in the gas. The drift field is established inside the tubes by a single high voltage supply, driving the central copper strip at  $10\text{ kV}$  with the others appropriately graded to ground with a resistor divider. The high voltage is monitored by measuring the leakage current though the Mylar to the grounded steel plates. The wire chambers, operated at approximately  $2\text{ kV}$ , are illuminated with an  $\text{Fe}^{55}$  source located a short distance down one of the tubes to verify their proper operation. They can also be illuminated by a high energy gamma emitter held outside the sealed module. Electronics to read out the device have been described elsewhere. [6,7] Briefly, signals from the anode wires and cathode pads are digitized every  $200\text{ nsec}$  by flash ADC's which store into a circularly addressed RAM for two full drift intervals ( $\sim 100\text{ }\mu\text{sec}$ ). The system is continuously active, except when a trigger halts the RAM clock and data compaction and logging takes place.

#### Performance

For module testing purposes, scintillators are used to trigger on the passage of cosmic rays. Figure 5 shows a typical through-going muon track in anode and cathode versus drift time views of the module.

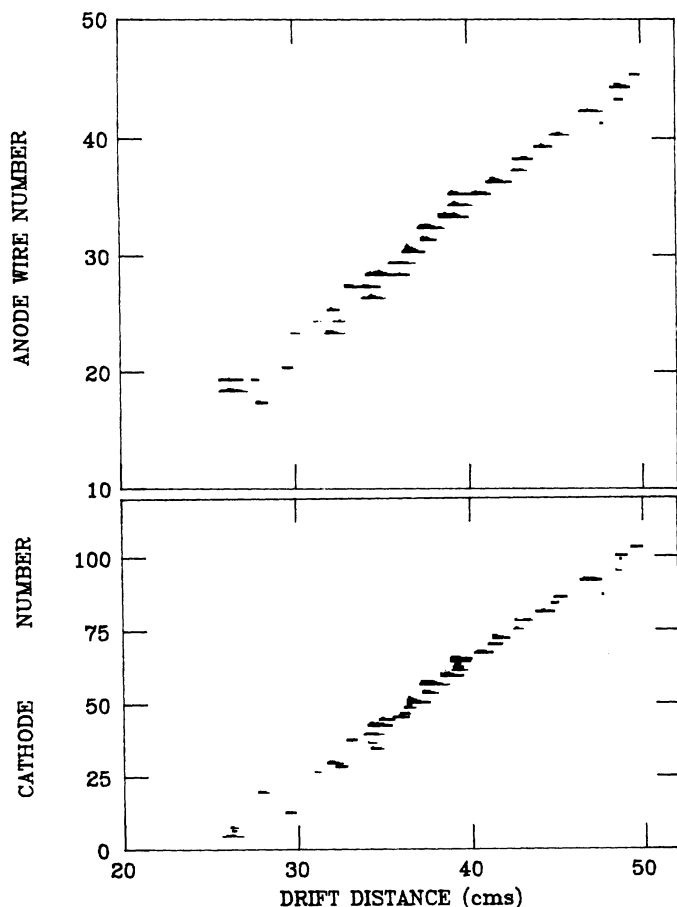


Fig. 5. Cosmic ray muon track recorded by a 5-ton module. The upper portion is the anode vs time projection; beneath it is the cathode vs time view. Ionization data are shown as miniature proportional pulses for each hit.

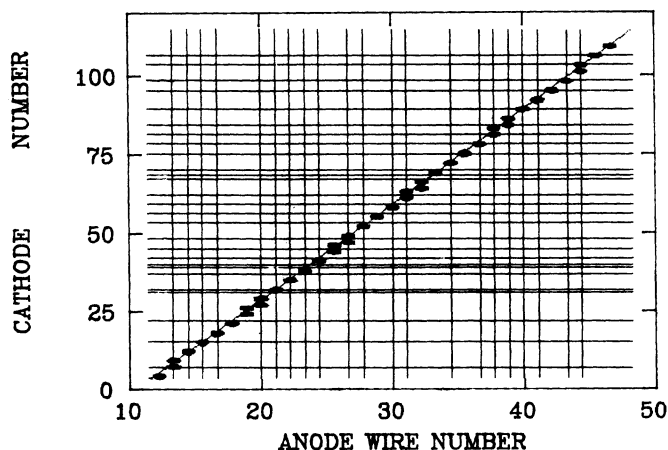


Fig. 6. Anode vs cathode view of the cosmic ray track in Fig. 5. Lines represent anodes and cathodes which have signals. Solid points show the tubes associated with anode-cathode pairs which have the same drift time. Three-dimensional event reconstruction uses such correlations to select the correct anode-cathode intersection from the large number of crossings shown.

Event reconstruction programs are able to determine the three space coordinates and the pulse height of each hit, which taken together provide a detailed record of each passing particle. Figure 6 is the reconstructed anode vs cathode view of a cosmic ray track. The vertical and horizontal lines represent channels with data. The solid points are the associated anode-cathode pairs correlated by timing. Pulse heights are also correlated, but have not been used in this matching.

More detailed analysis of performance has been completed so far only on data from a smaller prototype detector module, which differed from the full-sized modules mainly in the number of layers (70 instead of 256), the number of anode wires (53 instead of 63), and the drift distance (40 cm instead of 50 cm). Data were taken with this prototype for through-going cosmic-ray muons. In the analysis, matching of anode and cathode pulses has been carried out using drift times, and anode and cathode positions have been separately fit to straight lines.

Attenuation of drifting electrons in the prototype is examined in Fig. 7, which shows mean pulse height as a function of drift distance. Up to the maximum 40 cm drift distance of the prototype, the attenuation is seen to be consistent with that expected from diffusion alone. The attenuation of about 25% is stable and easily correctable offline. Tube efficiency is determined by predicting which tubes are traversed, using the fit parameters of each track, and comparing with tubes that have signals at the correct drift times. The resulting efficiency is shown vs drift distance in Fig. 8. It is observed that efficiency falls over the first 10 cm of drift distance to about 80% and falls only slowly at larger drift distances, suggesting that the effective aperture of the tube for drifting is a little smaller than the geometric aperture. This narrowing may come from the perturbation of the drift field by the finite-width copper strips that apply it; indeed the dips in the efficiency apparent in Fig. 8 are correlated with the positions of the copper strips.

Track fits can also be used to determine resolution in the drift direction by looking at residuals from the fit. A histogram of these is shown in Fig. 9. It has a FWHM of 7.2 mm and represents the combined effects of the sampling time equivalent to 2 mm, electronics rise time equivalent to 5 mm, and geometric imperfections of the detector. This histogram shows that the detector has as good or better spatial resolution in the drift direction as in the other two coordinates. Improvements in the final detector are expected to reduce the residuals' FWHM to about 5 mm. Uniformity of drift velocity is examined in Fig. 10, where the mean track residual is plotted vs drift distance. Except at the very largest drift distance, the mean residuals are small everywhere with a modulation of amplitude  $\sim 1$  mm, corresponding to the field distortions caused by the copper strip drift electrodes and leakage currents from the tubes to the steel through the Mylar.

### Conclusions

The completion of the first Soudan 2 detector modules is a milestone in the project. They demonstrate the basic feasibility of the honeycomb scheme, and have provided valuable experience in the fabrication and operation of this type of detector. The means of mass producing modules are now being finalized. Physics data collection will begin in 1986 with the first few hundred tons; completion of the full 1100 ton experiment is scheduled for 1988.

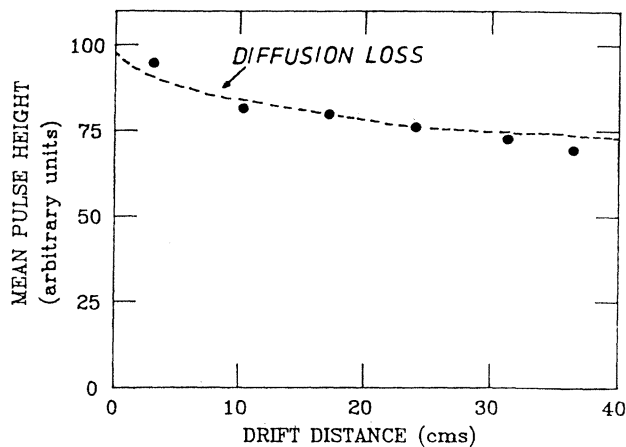


Fig. 7. Attenuation curve of prototype detector. Attenuation is consistent with calculation based on diffusion.

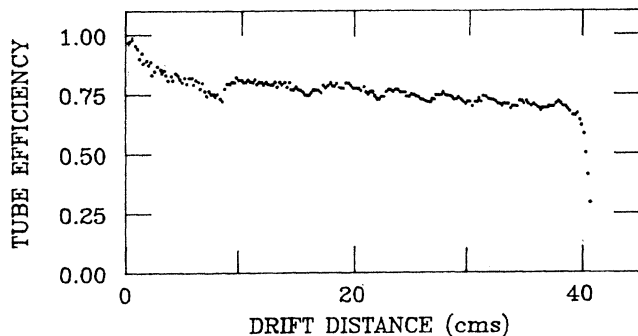


Fig. 8. Tube efficiency derived from fits to cosmic ray tracks in prototype detector.

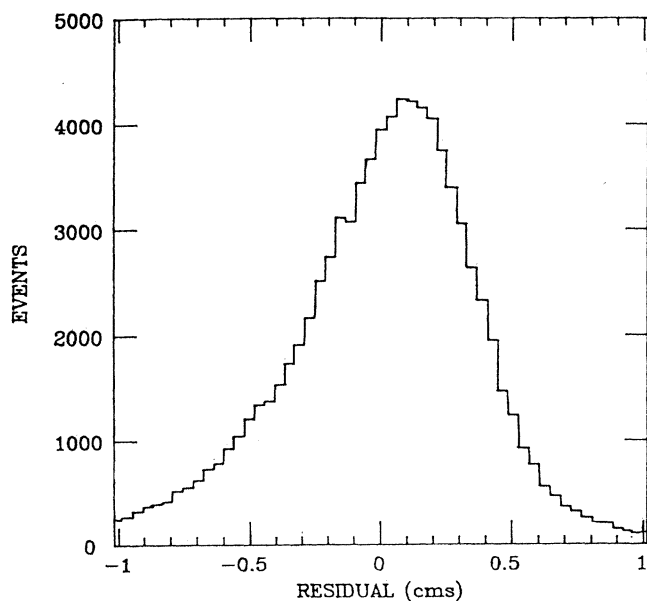


Fig. 9. Histogram of residuals from fits to cosmic ray tracks.

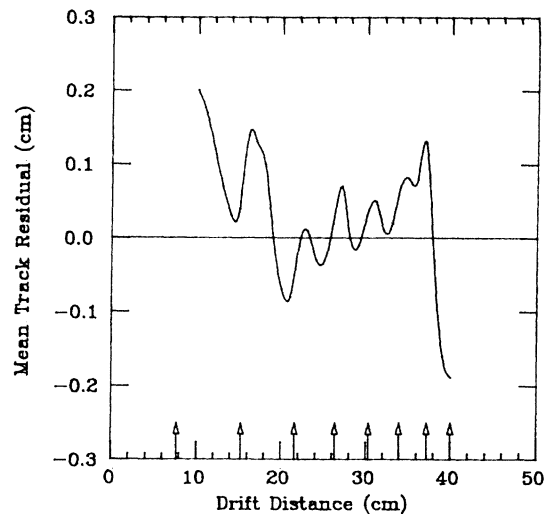


Fig. 10. Mean residuals from fits vs drift distance. The small mean residuals indicate a drift velocity that is nearly constant. Arrows show the positions of the copper equipotential strips. Variations in the residuals are caused by strip-width effects and leakage currents through the Mylar.

#### References

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