A DETECTOR FOR HIGH-ENERGY NEUTRINO INTERACTIONS

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ABSTRACT

We describe the design, construction and performance of a large mass detector used at CERN to study high-energy neutrino interactions in iron. This detector combines magnetic spectrometry and hadron calorimetry techniques.

Geneva - 8 June 1977

(Submitted to Nuclear Instruments and Methods)

^{*)} Supported by the Bundesministerium für Forschung und Technologie.

1. INTRODUCTION

The detector described here was prepared in conjunction with the new European accelerator, the Super Proton Synchrotron (SPS), which accelerates protons to 400 GeV. It is designed to study certain aspects of neutrino interactions in the energy range of $30 \text{ GeV} \leq E_\nu \leq 300 \text{ GeV}$. The mass of the detector is 1250 tons, with an effective target (fiducial) mass of ~ 750 tons. It is designed to measure, in the interaction of neutrinos with iron nuclei, the total energy of the hadron shower which may be produced, as well as the directions and momenta of muons which may be emitted. In particular, for the interaction

$$\nu + \text{Fe} \rightarrow \mu + \text{anything}$$

it will be possible to reconstruct all parameters of the so-called inclusive process. It will also be possible to isolate the neutral current processes

$$\nu + \text{Fe} \rightarrow \nu + \text{anything}$$

and, in conjunction with the narrow-band beam developed for the West Area Neutrino Facility, it will be possible to determine the ratio of the hadron energy to the neutrino energy, the "y" of the inclusive process. The detector has a large mass and, correspondingly, large event rates, good identification and momentum measurement of muons, and the ability to measure the total hadron energy, but it has a blindness to details of the hadron shower and an inability to identify electrons which may be produced and are of special interest. These characteristics make the detector complementary to bubble chamber ones which generally have opposite merits and demerits.

The apparatus (see Fig. 1) consists of magnetized iron modules, separated from each other by wire drift chambers. This constitutes the muon spectrometer capability of the detector. The magnetic modules are each constructed of a number of separate iron plates, between which scintillation counters are inserted. The scintillators sample the hadronic shower as it develops in the iron, and provide a "calorimetric" determination of the hadron shower energy. The iron or these modules therefore serves successively as a neutrino interaction target, as a calorimeter for the hadron shower, and as a spectrometer for the muons. This integration of the functions is a novel feature of this detector; its advantages lie in the acceptance solid angle for the muon spectrometer, and in the fact that it is economic.

This paper, together with anticipated papers on the SPS narrow-band neutrino beam and on the performance of the hadron calorimeter, are intended to help in the critical understanding of results which may be forthcoming from this detector.

2. MAGNET MODULES

2.1 Mechanical design

7x45x52cm
12x5x45cm

The detector consists of 19 magnetic modules. Each of these is constructed of circular iron plates, 3.75 m in diameter, with a 0.30 m central hole for the passage of the coil and with a total iron thickness of 0.75 m, corresponding to a weight (exclusive of supports and lifting provisions) of 65 tons. There are two types of modules: seven thin-plate modules, each consisting of fifteen plates, 5 cm thick, and twelve thick-plate modules, each consisting of five plates, 15 cm thick. The plates are attached to each other by means of stainless-steel strips welded at the top and bottom, and, in the case of the thin-plate modules, small spacers along the horizontal diameter, on both sides of the central hole and of the outer diameter. In order to maintain the homogeneity as a hadron calorimeter, the central hole, except for the 5 cm gap occupied by the coil, is filled with stainless steel. The coil consists of vertical turns, 15 up and 15 down, of water-cooled copper tubing. The power consumption is 20 kW per module at 1000 A. Figure 2 shows the principal dimensions for each type of module.

2.2 Magnetic field

The magnetization has been measured on the basis of the induced charge on pick-up loops threading a series of small-diameter holes parallel to the cylinder axis, or else threading the entire toroid. There were nine such holes, three each on a horizontal, a vertical, and a 45° radius, always dividing the iron into four equal sections. The results for the two types of modules are the same to within ~ 1%, so that a single result is presented here in Fig. 3. These results were obtained with the maximum magnetization current of 1000 A. With one-tenth of the power, or ~ 300 A, the field distributions are very similar but depressed by about 11%. The field lines are very nearly circular. Radially the field drops approximately 20% from the inner radius of 15 cm to the outer radius of 185 cm. The azimuthal dependence deviates from uniformity by approximately $\pm 1\frac{1}{2}\%$ owing to the localization of the coils in the vertical plane. The field strength, averaged over the surface of the magnet, is 16.5 kG.

3. DRIFT CHAMBERS

The muon tracks are followed in space by means of drift chamber planes between the magnet modules. The accuracy which is required, given the multiple scattering of the particles in the iron, is of the order of 1 mm. For chambers of this spatial resolution, drift chambers seemed to be less expensive than proportional chambers.

The chambers are hexagonal, with a distance between the parallel edges of 4 m, and are composed of three independent gaps. The right-left ambiguity and correct

association for multitrack events can be resolved with the three different drift directions. These directions are vertical, and at $\pm 60^\circ$ relative to the vertical. The spacing of sensitive wires is 6 cm and the gap width is 3 cm. Details of the chamber construction and associated electronics are described by Marel et al.¹⁾.

3.1 Electric structure of the chambers

The best electron collection and multitrack resolution are obtained with a uniform electric drift field. A good approximation to such a field can be achieved by means of cathode planes made of parallel equidistant wires at increasing potential. Highly accurate drift chambers of this type with 2 mm corrector wire spacing have been developed by Charpak et al.²⁾. A much simpler structure with a single anode wire, equidistant and parallel to the two cathode plates, has been adopted by Cheng et al.³⁾. For reasons of cost, we could not extend to chambers of the required dimensions the sophisticated solution of Charpak et al., and some problems also appear for multitrack separation¹⁾ with the simple cathode plane chambers. We have therefore adopted a half-way solution. An approximately uniform field along the 3 cm of drift space has been obtained by means of three potential corrector wires as shown in Fig. 4.

An important parameter for large chambers is the diameter of the sense wire: the efficiency plateau increases when the sense wire diameter decreases, but for a 4 m long wire the resistance of the wire is not negligible and introduces an attenuation of the pulse, which can be a factor 4 for a 20 μm wire, and reduces the plateau length by 200 V. For these reasons and also because of problems of mechanics, we have adopted 40 μm sense wires.

3.2 Chamber construction

Each chamber consists of four sandwich panels held by stainless-steel pins, enclosing the three sense wire planes described above (Fig. 5). These panels are composed of two aluminium skins, 1 mm thick, glued to a 20 mm wide aluminium honeycomb. The panels are reinforced by inserts all around the hexagonal perimeter and along the joints in the aluminium plate to resist the forces due to the clamping and to avoid gas leaks. The panels are separated by frames made of fibre-glass epoxy. The printed circuits on which the wires are soldered are glued on these frames.

During the construction a drilling jig is used to maintain the reproducibility and the position of panels and frames. The position of the wires with respect to the pins is kept to a precision of ± 0.3 mm. The system is sealed by O-rings, and the gas leak is less than 0.7 ℓ/hour per chamber at a pressure of 1 mbar. At this pressure the maximum deformation value of the panels is 0.2 mm (1.5 mm without the central insert).

3.3 Electronics

The organization of the read-out system is based upon the following considerations:

- i) It should be possible to resolve more than one track crossing the same drift cell.
- ii) The desired spatial resolution is ± 1 mm. This is coarse enough to permit direct conversion of drift-time by scalers and a ~ 100 MHz clock.
- iii) The SPS narrow-band beam spill is only 23 μ sec long. It is therefore necessary to have fast event buffering.

In order to take advantage of the low muon yield and yet not sacrifice multi-hits on the same sense wire, groups of sixteen non-adjacent sense wires are provided with four scalers for drift-time encoding. Each fourth wire is sent to the same time-to-digital converter (TDC) unit. In this way the sensitive area of the chambers is covered with a smaller number of scalers.

The data obtained during the short spill-length burst are stored in a 40-event, first in/first out (FIFO) buffer, until they can be read out via the CAMAC system.

The output pulses of the sense wires, at a level of 2.5-4 μ A, are preamplified on boards plugged directly into the chamber. Signals from these amplifiers are transmitted (40 m), via twisted-pair cables, to the TDC units in the counting room. The preamplifier circuit is shown in Fig. 6. The amplifier is a LeCroy^{*)} hybrid circuit (LD 6040), which has an adjustable threshold from 400 μ V to 2 mV.

The TDC units exhibit the following features:

- i) 16 input channels with enable/disable command;
- ii) 4 address/drift-time encoding possibilities per event;
- iii) 12 nsec resolving time between separate input signals;
- iv) direct conversion of drift-time with scaler, and 80 to 100 MHz clock frequency;
- v) fast reset for rejected events;
- vi) input signal acts as "start", trigger acts as common "stop";
- vii) analog output for number of hits per event;
- viii) 40-event FIFO buffer.

The circuit logic is shown in Fig. 7. The leading edge of the chamber signal is derandomized and used to open a gate for the scaler. There are four channels of scalers, and the input signals are priority encoded and latched. The "stop" is

^{*)} LeCroy Research Systems Corporation, USA.

provided by a suitably delayed trigger signal [late time reference (LTR)]. The typical maximum drift-time for the 3 cm drift cell is 610 ± 9 nsec and the LTR is delayed accordingly (800 nsec).

A "Load Buffer" command stores accepted events in the buffers in 500 nsec, and undesired events are discarded at this level by means of a "Reset" signal. In either case the inputs are again enabled.

The FIFO buffers are read out by CAMAC. Each drift chamber word uses 7 bits to encode the drift-time and 4 bits for wire address.

716 715 714
Wire Address 0000 1111
≤ 16 ≤ 64

3.4 Properties

The performance of these chambers has been studied in detail with a cosmic-ray set-up and has been further substantiated by measurements with muons in the final apparatus. Particularly relevant aspects such as efficiency, noise, and drift-time precision are summarized below.

i) Efficiency

The efficiency curves versus high voltage for three gaps are shown in Fig. 8. A lateral displacement of 3 m along the sense wires produces a shift of 100 V in the efficiency curve owing to attenuation in the wire. The plateau for operation is large enough to allow for this effect.

The efficiency is uniform along the sense wire (within the limits of the plateau) and is observed to be constant across the drift cell. The average efficiency over the chamber is typically 99.5% per gap.

ii) Drift-time linearity and precision

The measured drift-time for tracks perpendicular to the plane of the sense wires is to a good approximation a linear function of the distance to the sense wire, as shown in Fig. 9. Non-linear corrections arise for tracks which are inclined, and these corrections increase with the angle (Fig. 10).

The precision measured with the cosmic ray set-up is 0.95 mm. This error is due to nearly equal uncertainties in track position and drift-time measurement. Thus the spatial resolution is ≤ 0.7 mm (Fig. 11).

4. CALORIMETRY

The construction of a sampling calorimeter using plastic scintillator and photomultipliers for pulse-height analysis is straightforward. Precision pulse-height analysis using phototubes is, of course, notoriously complicated by the lack of intrinsic stability. For the control of the stability of the entire pulse-height chain, considerable care has been invested in the design of a system for calibration and monitoring.

The system for pulse-height analysis is characterized by three basic features:

- i) The scintillators are hodoscoped in 45 cm wide slabs in order to determine the average location of a hadron shower; the scintillators are viewed on both sides, and the ratio between the left and the right pulse height determines the position along the scintillator.
- ii) The sum of the right and left pulse heights is recorded separately for every scintillator, mainly in order to determine the longitudinal structure of the hadron shower and to correct for fluctuations in the fraction of π^0 's. This also permits the detection of soft radiation along the muon track and the identification of events in which the muon radiates a significant fraction of its energy.
- iii) The phototube gain and stability of the system is calibrated and continuously monitored using cosmic-ray muons.

The differential measurement of the hadron energy deposition leads to a large dynamic range in individual channels. The electromagnetic component of the shower gives rise to high track density, e.g. a shower with 100 GeV of π^0 's reaches a pulse height at the shower maximum that is equivalent to 500 minimum ionizing particles. Therefore the linear circuitry is designed to handle a dynamic range of 1:1000.

4.1 Scintillators

There are 145 planes of scintillators with pulse-height read-out, 105 planes in the initial seven 5 cm plate modules, and 40 planes in the following eight 15 cm plate modules. The last four modules are equipped with one plane of scintillators for triggering purposes only. The scintillators are 6 ± 1.5 mm thick, 45 cm wide slabs, eight per plane. The disposition of the scintillators in one plane is shown in Fig. 12.

Commercial plastic scintillator^{*)} type NE 110 is used. Since full-length pieces of the required size were not available, each scintillator has been made of two pieces glued together at the centre line. There are four different sizes of scintillator, with lengths between 228 cm and 372 cm. A 3 cm recess in the central scintillators leaves room for the magnet coil (see Fig. 12).

The light-guides are of an adiabatic type and of simple construction. The scintillators and light-guides are wrapped in a single layer of plastic/metal-foil sandwich^{**)} for light-tightness.

^{*)} Nuclear Enterprises Limited, Scotland.

^{**)} Marvelguard ECIA, Ludlow Corporation, USA.

All scintillators were tested before installation with a phototube mounted on one end. Pieces with an attenuation length below 1.2 m were rejected. The light transmission of all scintillators is carefully studied in the final set-up, using cosmic-ray data. No change in the attenuation length of more than 2% was found over a period of five months. A typical response curve is given in Fig. 13. The attenuation length is 2 m on the average, with a variation from one piece to another of 40 cm r.m.s. In general the attenuation is different for the two separate pieces of every scintillator. The step at the centre is due to the glued joint and is typically 10%.

From the fit of special cosmic-ray data, where only the right or left phototubes are operated, the parameters for attenuation length and the central steps are obtained. They are used in the normal runs as input parameters when the phototube gains are fitted from the right plus left summed output. Owing to local variations in scintillator thickness and homogeneity, and also to dispersion, the light output is not expected to vary purely exponentially with distance. The left plus right summed output signal can, however, be described fairly well by a catenary.

In general, the fitted parameters are different for the two halves, and the response is discontinuous at the centre. Figure 14 shows the average deviation between the measured pulse height and the fit for a large number of scintillators. The deviations are of the order of $\pm 2\%$, and are globally corrected.

4.2 Photomultipliers

The photomultipliers are 32 mm cathode diameter, type 150 AVP^{*)}. The tube bases are standard with 1 mm soft iron and mu-metal shielding against the fringe field of approximately 30 G. High voltage is supplied from a common bus, feeding voltage dividers with dropping resistances in series such that tube voltages can be adjusted individually in steps of 20 V. Before installation, the tubes were tested and sorted for approximately equal response to light produced at the centre of the scintillators. After the initial setting no further adjustment of tube voltages was necessary. The operation of 2400 phototubes did not cause severe problems. At the beginning of data taking, about 5% of the tubes had to be replaced because of their high noise level (dark current greater than 300 nA). The present exchange rate is about one phototube every other week, for the typical reason of high noise.

The tube sensitivity is on the average about 10 photoelectrons for minimum ionizing particles, or typically 8 photoelectrons for muons passing at the centre of the longest scintillator. Signal output is 0.1-0.2 mA for the minimum pulse height. The tubes are tested for linearity up to 300 mA. Deviations from linearity are typically +5% at 200 mA output current, and turn over to negative values for even higher anode currents.

*) Philips, France.

4.3 Signal processing

The processing of pulse-height signals is based on the idea that only one pulse height is recorded per scintillator, i.e. the outputs of the left and right phototubes are summed electronically before digitization. This leads to a more uniform response (see Fig. 13), and is economically preferable. In addition there is a smaller number of channels which record summed pulse heights on each side of every magnet module. This information is used to determine the horizontal position of the shower from the ratio of left to right pulse height. A combination of attenuated signals from non-adjacent scintillators is used to handle the case where the charge in one or a few particular channels is in the overflow.

The scheme for signal mixing is shown in Fig. 15 for one channel. Apart from the left plus right sum [labelled $\Sigma(L + R)$], 10% of the charge is sacrificed to sum both sides of one plane separately (labelled ΣL and ΣR), and another 10% to sum over odd and even numbered scintillators in this plane. After a further combination of suitable signals there are 1344 pulse-height channels for the 1160 scintillators.

Special ADCs have been developed with fast conversion and buffer storage for 40 events. The design is based on a commercial Wilkinson-type converter^{*)}, with a linearly rising discharge current, and 100 MHz digitizing rate. The resolution is ± 0.25 pC for a maximum charge of 250 pC.

The ADC response is described by a square-root law well matched to the statistical properties of a sampling calorimeter. The analog chain, including linear mixers and ADC's, is individually calibrated. Deviations from the square-root response are of the order of the resolution.

4.4 Monitoring

The scintillator light output and tube gain are continuously monitored using cosmic-ray muons for calibration. Cosmic-ray events penetrating several magnet modules are recorded between bursts of the neutrino beam. In this case a 30 dB amplifier built into the linear mixing circuitry (Fig. 15) is switched on. The relative gains of these amplifiers are measured with a mercury pulser using the test input of the mixers.

After amplification the muon signal is large enough for accurate measurement. The average muon pulse-height is analyzed off-line. Using a continuous unfolding procedure, the phototube gain is tracked with an accuracy of a few percent per channel for one day of data taking.

The long-term stability of the whole pulse-height system is again of the order of a few percent. The dependence of the calibration constants on the magnetic field polarity is of the same order.

*) LeCroy Research Systems Corporation, USA.

4.5 Calibration

All pulse heights are measured in units of an equivalent number of minimum ionizing particles. A test calorimeter placed in a hadron beam is used to obtain the conversion into hadronic energy, to study the resolution, and the longitudinal and lateral spread of the shower.

The calibration was found to be 12.6 equivalent particles per GeV, and the resolution is described by the formula: $R = \text{r.m.s.}/\text{mean} \approx 0.8/\sqrt{E(\text{GeV})}$. Complete results will be presented in a forthcoming publication.

5. THE TRIGGER LOGIC

5.1 General

The trigger decision is a two-step process. The fast trigger decision must be taken as soon as possible, since the fast trigger signal opens the ADC gates, and the phototube pulses are stored meanwhile in 250 nsec coaxial cables.

The so-called late trigger decision is taken later, and results either in a confirmation of the event -- and consequently the loading of the FIFO buffer -- or its rejection. Since a rejection cannot be performed before the ADC conversion has finished, which might take up to 2.6 μsec , a late trigger decision is not needed before, say, about 1 μsec after the fast trigger signal.

Whereas the fast trigger decision is based uniquely on scintillator information, also the drift chamber information is involved in the late trigger decision.

The fast trigger uses the sum signals over the right and left half of each module, a total of 38 signals. They are fed in circuits which perform i) a linear sum of the right and left sums of a module; ii) a fast amplification of the sum used for timing purposes, and iii) an integration with subsequent cable clipping of the linear sum, for use in pulse-height work. The integrated signals are fed into discriminators at different thresholds, thus forming the amplitude information on a modular basis, complementary to the timing information described above. The layout of the fast trigger logic is shown schematically in Fig. 16.

5.2 The cosmic muon trigger

The pulse-height response of the phototubes and associated circuitry is monitored by means of the signal of cosmic-ray muons recorded during the machine cycle between bursts. The cosmic muon trigger requires that a minimum number of modules be traversed.

In order to provide a bias-free calibration, the timing signals are grouped in two categories: one involves all modules with odd numbers, and the other all those with even numbers. The trigger requires a majority of three coincident hits

out of either 10 odd modules or 9 even modules. Thus the trigger requires in total at least five traversed modules, corresponding to a minimum energy of about 5 GeV. An event recorded with an "odd" trigger provides bias-free amplitude information on the even modules, and vice versa.

The flux of cosmic-ray muons is copious: the rate of downstream muons traversing at least five modules is about 80 per second over the whole apparatus. The illumination of the scintillators is relatively homogeneous (the rate is five times higher on the top scintillators compared to the bottom ones), with the exception of the lower front edge of the apparatus, since cosmic-ray muons go from top to bottom. For the first four front modules, special triggers for upstream muons are set up by delaying the signals of the contributing modules properly, with the understanding that the ADC contents for these "upstream" triggers are valid for one and only one module, where the ADC gate is correctly adjusted.

5.3 The fast trigger for neutrino events

Whereas the cosmic muon trigger is based uniquely on the timing information, the fast trigger for neutrino events involves the amplitude information as well. For each of the 15 upstream modules, discriminator levels are set at the following thresholds:

- a) one-muon level,
- b) hadron shower level on the basis of a single module.

In addition to this, the linear sums of all pairs of adjacent modules are formed, since hadron showers are likely to extend over two adjacent modules. For these 14 sum signals, 3 different hadron shower thresholds can be chosen.

The actual circuitry allows freedom in defining different possible trigger configurations. In general, the final trigger is an OR of several trigger modes, each mode being labelled by setting a special trigger bit.

5.4 The late trigger for neutrino events

The drift chamber hit information is used for a refined late trigger criterion. The maximum drift time is about 600 nsec, and 700 nsec after the fast trigger signal the information on the number of hits per drift chamber plane is available. Circuitry associated with the TDC determines whether or not at least one, two, three, or more than three hits occurred in at least two out of the three planes per drift chamber. This trigger aims at an efficient detection of multi-muon events. For example, a dimuon trigger could require at least two hits in at least two out of three planes, to be fulfilled in at least four consecutive drift chambers.

6. THE ON-LINE SYSTEM

6.1 The data acquisition

The data acquisition system can manage at a data-taking rate of 10 events per second. This enables the transfer of a maximum of 40 neutrino events and an equal number of cosmic muons during the 8.4 sec interval between successive spills.

The information of each event comprises 1344 ADC and 912 TDC channels, and a monitor block consisting of bit-patterns and scaler contents. All channels are equipped with FIFO hardware buffers, 40 events deep. All units involved comply with standard CAMAC rules. In the read-out of one event, the full information, i.e. about 2.5 Kwords, is transferred in about 8 msec in direct memory transfer mode to the on-line computer.

The on-line computer is a NORD-10 with 128K 16-bit words memory space. Its CAMAC multi-branch interface enables the addressing of up to 49 CAMAC crates, whereas the present system involves 40 crates.

6.2 Data reduction

Only a minor fraction of the pulse-height and drift-time channels carry useful information on a particular event, therefore a selection of such channels at the on-line level is performed. Only those TDC channels are retained which exhibit a non-zero drift-time. All such drift-times together with their respective wire-addresses constitute the drift-time information block of the event, and are written onto tape.

ADC channels are retained if the program detects a significant pulse height above the pedestal. Therefore, two files exist permanently, one representing the current pedestals for the cases where the μ -amplifiers are switched off (neutrino events), and the other where the μ -amplifiers are switched on (cosmic-muon events). In order to follow long-term variations of the pedestals, an updating procedure is used, based on so-called "pedestal events", taken regularly during each SPS cycle.

All non-empty information channels are used to fill histograms for on-line monitoring purposes. The total time needed for the program to treat one event is on the average 80 msec. The length of the events written on tape differs depending on the number of non-empty information channels. On the average, one 1600 bpi/9 track tape contains around 30,000 raw events.

6.3 On-line monitoring

Many histograms are filled during data taking, enabling an efficient check to be made of the functioning of the whole electronics system. For the pulse-height channels, the most useful ones are the displays of the ADC pedestals and of their variations. The latter allow easy detection of "noisy" phototubes. Analogously,

for all wires of the drift chamber system, hit-frequency distributions are offered as well as drift-count distributions of the TDCs, to mention only the most important ones. An on-line event display is available as well.

In parallel with the data taking, a multiplexer scans about 700 voltage levels for monitoring purposes, with different frequencies but at least once every two hours.

The computer is linked to the neutrino beam control computers, which at each burst provide a set of standardized pieces of information on the beam parameters. This information is accumulated and dumped regularly onto tape.

7. OFF-LINE DATA REDUCTION

7.1 Organization of data processing

- i) The on-line data acquisition computer writes raw data tapes, which contain neutrino triggers taken during the spill and cosmic-muon triggers taken between bursts.
- ii) The calibration program reads the raw data tapes, processes cosmic μ 's, and updates the values of pulse-height calibration constants. Physics split-tapes are written, containing only ν triggers together with current values of relevant calibration constants.
- iii) The reconstruction program reads physics split-tapes and performs the reconstruction of μ 's present in the events and the calculation of the energy (in number of equivalent particles) collected in each scintillator plane of the calorimeter. Data summary tapes are written containing, for each ν trigger, the complete original information plus the result of reconstruction.

7.2 The reconstruction program

7.2.1 Muon track pattern recognition

The digitizings of the drift chambers are associated to form track candidates, solving the intrinsic mirror ambiguity of the drift chambers, and separating the true coordinates from physical (δ -rays) and instrumental (double hits) noise.

The basic pattern recognition loop performs space association of coordinates on three adjacent drift chamber modules (nine planes). Parabolic approximations in the three views (y , u , v) combined in space can be expressed, thanks to the geometrical symmetry of the chambers, as three linear constraints on the nine coordinates involved. The orthogonality of the bending plane to the magnetic field vector is used as an additional constraint. Continuation of the track in subsequent modules relies on the same criteria.

If several choices are possible for the same track, they are carried through and a final decision on which one to select, is taken on the basis of smoothness.

7.2.2 Muon track parameters' estimate

To compute momentum and angle of muon tracks, the following algorithm⁴⁾ is used:

- a) A track is defined by five parameters:

x } position of the intersection of the track
 with a fixed reference plane $z = z_0$,
 y } perpendicular to the spectrometer axis.

dx/ds }
 dy/ds } at the same plane $z = z_0$
 $1/|p|$ }

- b) Starting from approximate initial values of the five parameters, the corresponding track is propagated in the spectrometer, according to the equations of motion in the magnetic field (including average energy loss), and impact coordinates with drift chamber wire planes are obtained.
- c) The minimization of the χ^2 of the differences between impact coordinates and real measured coordinates, computed with a covariance matrix that takes into account the dominant contribution of multiple scattering as well as measurement precision, yields corrections to the initial parameters of the track.

The minimization procedure (b) and (c) is repeated until convergence is reached (in most of the cases two iterations are enough).

- d) The muon is back-tracked from z_0 to the vertex plane. In the case of low-momentum muons that are absorbed in the spectrometer, the absolute value of the momentum is calculated also from range.

7.2.3 Calorimetry

Pulse heights collected in the scintillators are converted into the number of equivalent particles, taking into account, for each individual scintillator, the photomultiplier sensitivities and scintillator absorption length, having determined the centre of gravity of the deposited energy in each module from the sum of the pulse heights of the left and right halves.

8. NARROW-BAND BEAM MONITORING

The determination of neutrino cross-sections requires knowledge of the neutrino fluxes. Knowing the fluxes of pions and kaons, the ν flux can be calculated. There is no known method of measuring directly the absolute intensity of π 's and K's in a high intensity beam of both particles. The determination of the absolute intensity, and the determination of the relative amounts of π^+ , K^+ , p (π^- , K^-) in the positive (negative) parent beam are therefore carried separately.

To measure the absolute intensity, a beam current transformer at the upstream end of the decay tunnel is used. This device is calibrated with a current pulse to 1%. The resolution threshold is dependent on the duration of the spill. It corresponds to 2×10^6 particles in a spill of 23 μ sec.

Another monitor, which measures the beam intensity in a completely different way, is a thermally isolated iron block of three tons ($50 \times 50 \times 150 \text{ cm}^3$). This calorimeter located downstream from the decay tunnel, is built into the μ shield. The energy deposited by the beam heats the block and the temperature rise is measured by Pt resistors. The calorimeter is calibrated by electric heating. A temperature rise of 3.0°C in 100 hours and a steady-state temperature difference of 4.8°C with respect to the surroundings are measured when heated by 21 W. Relative changes of the temperature difference between the calorimeter and the outside are measured with a precision of 10^{-3} ; the resolution threshold of changes in temperature is 2×10^{-3} .

The beam composition is measured by a differential Čerenkov monitor at the upstream end of the decay tunnel. Helium serves as the radiator gas (1.9 m). A diaphragm accepts photons, which are produced at angles $< 1 \text{ mrad}$ with respect to the axis of the monitor. The diaphragm is at the focus of a spherical mirror. The monitor can be tilted in two directions to make it parallel to the beam line.

Čerenkov light of one kind of particle is accepted by the diaphragm only within a certain pressure interval of the radiator gas. Thus by plotting the light response versus pressure, different kinds of particles show up in bumps. The area under a bump is proportional to the number of corresponding particles in the beam.

Pressure curves are taken each time the beam parameters are changed.

In addition to the above monitors, some others are installed in the beam line. Before and after the decay tunnel there are grid ionization chambers and secondary emission grids to measure the profiles of the parent beam; from these the beam direction and the divergence are deduced. Another ionization monitor measures the profile of the muons after the first 10 m of iron shielding.

The target efficiency is obtained from secondary emission monitors, installed upstream and downstream from the target.

All information from the beam monitors, as well as information on the beam itself, is collected in the beam computer. The data is put in predefined blocks, which are sent on request to the computer of the experiment.

Acknowledgements

The realization of this detector was only possible thanks to the skill and dedication of the many people having collaborated on the various aspects of it. They are, at CERN: W. Albrecht, J. André, A. Cyvoct, M. Invernici, M. Morpurgo, G. Pozzo (magnet design, assembly and measurements); B. Danner, L. Jost (magnet power supplies); R. Famy et al. (scintillators); M. Schmitt, J. Dozio (building and installation); G. Juban (installation); W. Coosemans, E. Menant, C. Prodon (survey); H. Atherton, P. Lazeyras et al. (beams); G. Stefanini, O. Runolfsson (monitoring). At Dortmund: H. Büttner, W. Horath, H. Noffke, T. Villett (scintillators). At Heidelberg: E. Fahländer, G. Gastall, J. Grundinger, G. Gumbin, H. Maier, R. Megele, G. Moser, R. Mush, W. Scherz, K. Schmitt, I. Steigleder, T. Steigleder, E. Ulses, E. Wolfgramm (phototubes and electronics). At Saclay: S. Bréhin, C. Leschevin, H. Martin, A. Patoux and J. Pelle (drift chambers and electronics).

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Figure captions

- Fig. 1 : Layout of the neutrino experiment.
- Fig. 2 : Mechanical detail of a magnetic module.
- Fig. 3 : Results of the magnetic field measurements with 1000 A magnetization current.
- Fig. 4 : Wire structure of the drift chambers. S.W. is the sense wire, POT.W. are the potential wires.
- Fig. 5 : Mechanical details of a drift chamber.
- Fig. 6 : Diagram of a drift chamber amplifier.
- Fig. 7 : Block diagram of a time-to-digital converter.
- Fig. 8 : Efficiency and multiple triggers as a function of sense wire high voltage.
- Fig. 9 : Drift velocity in one gap.
- Fig. 10 : Difference in drift-time between the measured time and the theoretical time versus the distance of the track to the sense wire, for different incident angles. The theoretical time is defined by fitting a straight line on the measured times for normal tracks ($\theta < 5^\circ$).
- Fig. 11 : Spatial resolution of the chamber for normal tracks: distance between the observed position on the chamber and the position defined by auxiliary multiwire proportional chambers.
- Fig. 12 : Disposition of the scintillators in one plane.
- Fig. 13 : Light transmission of a typical scintillator. The attenuation lengths from the left end, from the right end, and from the sum of both ends are shown.
- Fig. 14 : Average deviation between measured pulse height and a fit for a large number of scintillators.
- Fig. 15 : Pulse-height linear mixing circuitry.
- Fig. 16 : Diagram of the fast trigger logic.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

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Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

amplifier for stereo
12-bit DAC

Fig. 16