A DETECTOR FOR NEUTRAL-CURRENT INTERACTIONS
OF HIGH-ENERGY NEUTRINOS

(CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration)

A.N. Diddens, M. Jonker, J. Panman and F. Udo
NIKHEF, Amsterdam, The Netherlands

J.V. Allaby, U. Amaldi, G. Barbiellini¹⁾, A. Baroncelli, V. Blobel²⁾,
G. Cocconi, W. Flegel, W. Kozanecki, E. Longo, K.H. Mess, M. Metcalf,
J. Meyer, R.S. Orr, F. Schneider, A.M. Wetherell and K. Winter
CERN, Geneva, Switzerland

F.W. Büsser, P.D. Gall, H. Grote, P. Heine, B. Kröger, F. Niebergall,
K.H. Ranitzsch and P. Stähelin
II. Institut für Experimentalphysik der Universität^{*)}, Hamburg, Germany

V. Gemanov, E. Grigoriev, V. Kaftanov, V. Khovansky and A. Rosanov
ITEP, Moscow, USSR

R. Biancastelli⁴⁾, B. Borgia³⁾, C. Bosio⁴⁾, A. Capone³⁾, F. Ferroni³⁾,
P. Monacelli³⁾, F. de Notaristefani³⁾, P. Pistilli³⁾,
C. Santoni⁴⁾ and V. Valente⁵⁾
INFN, Rome, Italy

(Submitted to Nuclear Instruments and Methods)

-
- 1) On leave of absence from the Laboratori Nazionali INFN, Frascati, Rome, Italy.
 - 2) On leave of absence from II. Institut für Experimentalphysik, Universität Hamburg, Germany.
 - 3) Istituto di Fisica dell'Università di Roma and INFN, Sez. di Roma, Italy.
 - 4) INFN Sez. Sanità and Istituto Superiore Sanità, Rome, Italy.
 - 5) Laboratori Nazionali INFN, Frascati, Rome, Italy.
 - *) Supported by the Bundesministerium für Forschung und Technologie, Bonn, Germany.

ABSTRACT

The construction and performance of a large detector, designed principally to investigate neutral-current interactions of high-energy neutrinos, are described. The detector consists of an ionization calorimeter as a target to determine the energy and the direction of the shower produced by the neutrino scattering, and of a magnetic muon spectrometer. The calorimeter has also been used as a muon polarimeter.

1. INTRODUCTION

The detector described in this paper has been built for use with the neutrino and antineutrino beams at the CERN 400 GeV Super Proton Synchrotron (SPS). The detector is principally designed to investigate the neutral-current interactions of high-energy neutrinos and to determine their strength and structure. In particular, it is possible to separate the neutral-current processes

$$\nu_{\mu} + N \rightarrow \nu_{\mu} + \text{hadrons}$$

from the charged-current interactions by ensuring that no muon is produced and to measure the total energy and direction of the hadronic jet produced by the neutrino scattering. In narrow-band neutrino beams these measurements, in conjunction with the neutrino energy, make it possible to reconstruct the kinematical parameters describing this inclusive process and to determine the momentum transfer Q^2 and the fractional energy transfer y from the incident neutrino to the hadronic jet.

It is also possible to isolate the neutral-current processes induced by the interaction of neutrinos with electrons:

$$\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-},$$

and to measure the energy distribution of the electrons.

The detector consists of a fine-grain target calorimeter composed of 78 equal subunits, surrounded by a frame of magnetized iron for muon identification at large angles; it is supplemented by a muon spectrometer. A schematic view is shown in fig. 1. The fine-grain calorimeter, consisting of marble target plates interspersed with hodoscopes of scintillation counters and proportional drift tubes, is designed to sample the particle shower as it develops in the target plates, and to measure the shower energy and direction. Proportional drift tubes also measure the direction of muons and their deflection in magnetized iron, and sample that part of hadron showers which may escape from the target calorimeter into the iron frame or into the muon spectrometer.

The separation of the hadron and the muon measurements allows accurate calorimetric measurements in the fine-grain target core, and good identification and detection of muons, with large solid angle acceptance, in the surrounding iron frame and muon spectrometer. The fine-grain calorimeter has an effective target weight of ~ 180 tons and provides adequate event rates. Owing to calorimetric energy measurements, it is insensitive to details of the hadronic final state. The characteristics of the detector are therefore complementary to those of bubble chambers [1], and to those of massive neutrino detectors such as the one of the CDHS Collaboration [2].

The calorimeter has also been used as a muon polarimeter. Positive muons produced by antineutrinos in the massive neutrino detector of the CDHS Collaboration located in front of this detector may stop in one of the marble plates. When the surrounding iron frame is magnetized in a dipole configuration it provides a weak magnetic field inside the target calorimeter, perpendicular to the beam direction in which the spin of stopped muons precesses. The decay positrons then show the characteristic forward-backward asymmetry with respect to the muon spin.

This paper, together with others on more special aspects of the apparatus, for instance on the performance of the proportional drift tubes [3] and of the calorimeter itself [4], is intended to help in the understanding of physics results which are currently being obtained using this detector.

2. THE TARGET CALORIMETER

2.1 Calorimetry

The kinetic energy of hadrons produced in the interaction of neutrinos is determined from the ionization loss sampled by plastic scintillation counters between the target plates. The precision and stability of this measurement is determined by the quality of the pulse-height analysis of the photomultipliers. We have developed a system which guarantees gain stability and correction for light attenuation in the scintillators by using the information on location given

by the hodoscopes of scintillators and proportional counters and a calibration and continuous monitoring of pulse height by the energy loss of cosmic-ray muons.

The sampling of single muons and electron tracks and of high-energy hadron and electron showers requires a large dynamic range. At the shower maximum a 200 GeV hadron shower can, in a single scintillator, give a pulse height that is equivalent to 150 minimum ionizing particles. Pulse-height measurements on single particles require about 30 pulse-height channels to match the measurement errors and the fluctuations due to photoelectron statistics. Therefore the pulse-height analysis chain for the scintillators is designed to handle a dynamic range of 1 : 5000.

The ionization loss of hadron showers developing in the iron plates of the frame magnet or of the magnetized end calorimeter is sampled using proportional counters. The use of proportional counters in calorimetry is not new. Murzin [5] has described a calorimeter using proportional counters for the detection of cosmic radiation. The space-charge screen of positive ions produces a dependence of the gas amplification on the track angle. In addition, low-energy tracks at a large angle are not stopped by range (as, for instance, in plastic scintillators) and can, therefore, produce large fluctuations in pulse height. In calorimetric measurements these effects are expected to average out and to be adequately described by an over-all calibration constant. They do, however, contribute to fluctuations in detected energy and hence affect the energy resolution. The counters we have developed have uniform response to within $\pm 5\%$ over 100 layers of $4 \times 4 \text{ m}^2$ surface area, a property which is more difficult to achieve with scintillation counters. For the sampling of single-particle tracks and of high-energy showers, a dynamical range of 1 : 50 is sufficient because of the larger pulse-height fluctuations in proportional counters and of their smaller cross-section.

The direction of the energy flow of showers [6] in a calorimeter can be determined by sampling the lateral distribution of ionization loss between the calorimeter plates. The origin of the shower, the neutrino interaction point, is determined using the position and the pulse-height information of the proportional

drift tubes in the initial part of the shower; the centre of energy deposition (barycentre) of the shower energy is determined mainly using the position and pulse-height information of the scintillator hodoscopes.

The plate thickness and material, and the width of the detector elements, have been chosen to optimize the measurement of the energy and the direction of the hadron shower. For the hadron energy we require a resolution which is comparable to the uncertainty in the neutrino energy as inferred from the narrow-band neutrino beam; hence we require $\Delta E_H < 10 \text{ GeV}$ at the maximum energy envisaged, $E_H = 200 \text{ GeV}$. The precision of the hadron shower direction measurement is limited by the intrinsic fluctuations of the shower and, in addition, by the measurement error.

The plate material has to be chosen for approximately equal lengths of hadronic and electromagnetic showers so as to minimize fluctuations of shower length. This amounts to the requirement

$$12X_0 \approx 3\Lambda ,$$

or $\Lambda \sim 4X_0$, where X_0 is the radiation length and Λ the absorption length. The solution adopted in this detector consists of a modular construction with 8 cm thick marble plates of density $\rho = 2.75 \text{ g/cm}^3$ followed by a plane of scintillation counters and a plane of proportional drift tubes, rotated by 90° with respect to the scintillation counters. The average density is 1.3 g/cm^3 , the average radiation length 20 cm, and the average absorption length for pions is 93 cm.

2.2 Modular construction

The calorimeter consists of 78 subunits. Each of these is constructed of a marble plate, with $3 \times 3 \text{ m}^2$ surface area and 8 cm in thickness, surrounded by an iron frame of the same thickness and of 45 cm width, which is magnetized in a toroidal configuration by two coils on the vertical parts of each frame. Figure 1 is a perspective view of the last 12 modules showing some details of construction.

The bottom part of each iron frame is U-shaped, fabricated from three pieces welded together. The top is closed by a simple slab, and the elements are fixed

together to form a square frame. The spacing between subunits is 20 cm. The marble plates are held by lugs within each iron frame.

Each coil is formed by two hollow, water-cooled copper conductors. The water flows in opposite directions in the two conductors so that the average temperature increase ($\sim 4^\circ$) is about the same along the whole length of the coil. This minimizes the temperature gradients, which otherwise would affect the amplification of the proportional drift tubes when the magnet is powered. When the two coils act in the same sense, 1000 A provide a toroidal field of 1.4 T in the iron frame. When connected in opposition, the two coils produce a rather homogeneous vertical field of 58 G in the volume occupied by the marble.

The target plates are interspersed with arrays of 20 scintillation counters of 3 m length and $15 \times 3 \text{ cm}^2$ cross-sectional area, and of 128 proportional counters of $3 \times 3 \text{ cm}^2$ cross-section and 4 m length. Both scintillators and proportional counters alternate in the horizontal and vertical direction. The scintillation counters cover only the target plates, while the proportional counters cover the whole of the target plates and the iron frames.

The outer 16 proportional drift tubes on each side sample the energy of showers which develop in the iron frames. The iron frame thus serves as a coarse hadron calorimeter, as a muon filter, and as a muon spectrometer.

2.3 The magnetic field in the iron frame

The magnetization of the iron frames with the coils connected for a toroidal configuration has been measured by the induced charge on pick-up coils wound around the four legs of three different frames, as depicted in fig. 2. The results for the three frames are the same within $\pm 1\%$. The field is constant to within $\pm 1\%$ at the three positions measured along each leg; in the vertical legs it is increased by 6% owing to the presence of the coils. At the standard magnetization current of $\sim 1000 \text{ A}$ the mean field values are 14.5 kG in the top and bottom legs and 15.4 kG in the lateral legs. In the corners matching the horizontally and vertically oriented legs, the field is assumed to vary approximately

linearly between these two values. With one-half of the magnetization current the field is 14.5% smaller.

In the dipole configuration of the coils, the magnetic field at the surface of the target plates was measured using a Hall probe. The resulting field component, vertical to the incident beam line, has a mean value of 58 G and was found to vary by less than 1 G over the volume used for polarization measurements.

2.4 The scintillation counter system

The geometry of the calorimeter led to a disposition of 1560 scintillators of transverse dimensions $300 \times 15 \text{ cm}^2$, distributed over 78 planes of area $3 \times 3 \text{ m}^2$, each plane thereby containing 20 scintillators. The detailed design of the system was motivated by four considerations: i) precise measurement of single-particle ionization; ii) accuracy in the measurement of total energy deposition by hadronic and electromagnetic components of a shower; iii) provision of a substantial mass of sensitive material to provide an active target for subsequent development of the apparatus; iv) ease and reliability of operation.

These conditions were met by the use of 3 cm thick polyvinyl toluene scintillators, NE114, terminated with a plane mirror at one end and viewed from the opposite end, through a 50 cm long triangular light-guide, by a single 2", 12-stage, photomultiplier, EMI 9839A. The total mass of plastic scintillator thus provided is about 21 tons.

Figure 3 gives a typical pulse-height distribution for high-energy muons passing through the centre of the scintillator. The width of the distribution indicates that a minimum ionizing particle yields 56 photoelectrons.

The light attenuation properties of each scintillator were measured, before installation, with a scan by a ^{106}Ru β -ray source, the current of the photomultiplier being measured as a function of the distance between the source and the end of the scintillator. Figure 4 shows a typical response curve, indicating an excellent transparency, in that the variation over the 3 m length is less than 30%. The response at the distance x from the light-guide may be represented

analytically by the formula

$$f(x) = K \left[e^{-x/\lambda} + \rho e^{-(2L-x)/\lambda} \right], \quad (1)$$

where K is a constant, ρ a reflectivity coefficient ≈ 0.8 , λ the scintillator attenuation length, and L its physical length.

A fit of eq. (1) to the data contained in fig. 4 gave $\lambda = (3.9 \pm 0.2)$ m. In the selection of scintillators used in the calorimeter, only those with $\lambda \geq 2.7$ m were used. Figure 5 gives the over-all distribution of attenuation lengths for the total scintillator population; the peak lies around 3.8 m and the distribution falls rather steeply on the low side with a $\Delta\lambda$ of about 1 m.

While providing a physical description of the scintillator properties, formula (1) did not always provide a very good fit to the data. It was found that a simple quadratic form

$$f(x) = A + Bx + Cx^2, \quad (2)$$

with A, B, and C being fitting constants characteristic of the scintillator, gave in general a very good fit. Figure 4 shows an example of a fit of eq. (2), and fig. 6 gives the distribution of the r.m.s. deviation of the fit from the measured attenuation for several hundred scintillators. Formula (2) was thus adopted, and a computer file containing the constants of the whole scintillator population was prepared and updated at regular intervals. These data were subsequently used, as described in Section 7, to correct the scintillators' response with respect to the position of the detected particles. The constant revision of the scintillator properties was found to be essential, as the light transmission of the NE114 deteriorated continuously at a rate of about 1.5% per month.

In order to ensure a uniform sensitivity throughout the detector, the scintillators were matched in a very simple fashion to the photomultipliers. The product $f_i(280) \cdot Q_i$ [where $f_i(280)$ is the β -ray response of scintillator i 280 cm from the light-guide, and Q_i is the quantum efficiency, given by the PM manufacturers] was kept constant by a suitable choice of the PM. This elementary procedure yielded a sufficiently good uniformity over the whole detector.

2.5 Photomultipliers

The photomultipliers (EMI 9839A manufactured to match the requirements of this calorimeter) have a useful cathode diameter of 45 mm, 12 dynodes, and an effective quantum efficiency greater than 15% for blue light. The tube sensitivity is on the average 46 photoelectrons for a minimum ionizing particle crossing a scintillator at the mirror side. Setting the gain to 2×10^6 gives an output of 7.5 pC at the anode. For the typical pulse width of 15 ns the current is 0.8 mA and the pulse height on an impedance of 50 Ω is 40 mV. For ionization corresponding to 400 minimum ionizing particles, the anode pulse has a charge of 3000 pC. On the average, the 1600 photomultipliers deviate by less than 1% from linearity at this pulse height, thus meeting the dynamic range requirement.

The noise rate at a discriminator setting corresponding to $\sim 1/5$ of a minimum ionizing particle is a few hertz and is stable over long periods.

The product of gain and sensitivity has been equalized to within $\pm 20\%$ with the help of resistors in series with the high-voltage supply, thus allowing all the 120 tubes belonging to six consecutive subunits to be operated at the same supply voltage. The resulting distribution for a sample of 600 photomultipliers is shown in fig. 7.

The stability of the gain is monitored using the cosmic-ray tracks which are recorded between accelerator pulses. Over a period of 10 days we observe an average drift of 0.6%. It is therefore possible to monitor the product of gain and sensitivity with an accuracy of better than 1%.

2.6 Processing of photomultiplier signals

The analogue signals produced by the photomultipliers are processed as shown schematically in fig. 8.

Twisted-pair cables are used, composed of 10 twisted pairs, each with its own insulation sleeve and surrounded by a common copper shield. This cable [7] has an impedance of 100 Ω , a rise-time of 15 ns, and a cross-talk of charge between any two pairs of less than 10^{-4} after 30 m of transmission.

Signals from the anode and the last dynode of the photomultipliers have been combined to drive the twisted-pair cable in a balanced mode, as shown in fig. 9. The cable length between the photomultipliers and the signal splitters, which are located in the control room, was adjusted to ensure that signals from a relativistic particle travelling through the centre of the calorimeter in the direction of the neutrino beam are coincident in time at the splitter to within ± 2 ns. The dotted lines in fig. 8 indicate circuits which are repeated 20 times on the board; the splitter has 20 inputs and 2×20 outputs, one of them connecting to a discriminator system which is used for trigger purposes and the other to a system of ADCs for pulse-height analysis. Not shown are a special input for test purposes and two analogue sum outputs giving pulses proportional to the sum of all scintillators in one plane.

This splitter board is contained on a module of NIM size and a single CAMAC bin width. Twenty modules are combined on one crate of NIM dimensions, thus containing 1260 signal connections using multipin twisted-pair connectors.

The main signal travels towards the input circuit of the ADCs via an 80 m long twisted-pair cable. This delay is required for the trigger logic to generate gating pulses for the ADCs in time with the arrival of the signals to be analysed. An isolating (1 : 1) transformer is used to adapt the balanced signal of the twisted-pair cable to the single end input of 100Ω impedance of the ADC. The signal is divided, 95% being analysed by one 8-bit ADC and 5% by another 8-bit ADC, thus providing a range of pulse-height analysis of 5000 channels. The ADCs have a sensitivity of 0.25 pC per channel, and the pedestals have been adjusted to channels 4-8. The range of 5000 channels corresponds to ~ 150 minimum ionizing particles (mip) of a shower crossing one scintillator; this situation occurs on one of the scintillators at every hundred 200 GeV showers.

The ADCs have a buffer storage for 50 events. The design is based on a commercial charge-to-time converter^{*)} with linearly rising discharge current and

^{*)} LeCroy Research Systems Corporation, USA type QT 100 D.

30 MHz digitizing rate. The total conversion time is less than 12 μ s. Ten ADC channels are combined in one CAMAC module.

The ADC response, including the splitter and divider, is individually calibrated. Deviations from linearity are found to be less than 2%.

The discriminator system contains logic for strobing, holding, resetting, or reading the information of each event. The hold function is used to memorize the event pattern while a trigger decision is taken. If the event is accepted by that decision, the information is retained and read into a fast buffer memory, otherwise it is reset after 400 ns. The fast buffers are read out via CAMAC, together with all other event information.

2.7 Proportional drift tubes

The experiment is equipped with 96 layers of proportional drift tubes, each layer covering $4 \times 4 \text{ m}^2$; 78 planes are in the target calorimeter, 18 planes in the muon spectrometer. Every third and fourth plane of each projection is shifted laterally by one-half wire distance for solving the left-right ambiguity of tracks. The proportional tubes are required to locate muon tracks with an accuracy of 1 mm (r.m.s.) and to measure the energy of particle showers by sampling the ionization loss of the secondaries in the marble, in the iron frames, and in the end calorimeter. This double purpose requires a dynamic range of about 50 and hence good stability of the gas amplification and of the electronic gain. This implies tight mechanical and electronic tolerances and a special stabilization of the gas amplification; the details of this part of the detector are described elsewhere [3].

Each chamber is built of 16 extruded aluminium tubes, of square internal cross-section $29 \times 29 \text{ mm}^2$, which are glued together with epoxy to form one unit. A stainless-steel sense wire of 50 μ m diameter is stretched along the centre of each tube with a tension of 1 newton = 100 g weight. The wire is placed inside narrow slots in cylindrical metal rods (one at each end) and crimped with a specially designed tool. Insulator pieces are fitted into both ends of each tube.

They hold the wire supports (i.e. the rods) and centre them to within ± 0.2 mm. The distance between the centres of two adjacent tubes of one chamber varies by less than ± 0.1 mm. A hole is left in each insulator piece for eventual replacing of the wire and for the gas flow. Two identical end-pieces made of h-shaped aluminium profile are glued over both ends of the chamber. The ends of the profiles are closed with pieces of aluminium sheet which are glued on.

In each of the end-pieces there are 16 circular holes for access to the wire supports (for electrical connection and for the possibility of changing a broken wire *in situ*). Rubber seals are placed around each hole, and the end-pieces are then firmly sealed by a metallic cover-plate to ensure gas-tightness. On one side of the chamber the wires are connected to a printed-circuit board.

The gas inlet and outlet connections are on the same end as the connectors to the wires. Immediately after entering the chamber unit a laminar gas flow is established by a deflector plate. The gas flows down the first eight tubes and back through the second eight tubes.

The chambers have a centring hole at one end and a centring slot at the other, with respect to which the wire positions are known to within 0.2 mm. Eight chambers are mounted together to form one layer of 4×4 m² surface area.

The electronics system records the charge collected at the sense wire and the drift-time for particles traversing a tube. A detailed description of this system will be given elsewhere [8]; only the general features are considered here.

Each wire is connected to a charge amplifier. The charge- and time-measuring electronics are self-triggering on the first bit of charge, 0.25 pC. An external gate signal, derived from the scintillation counters, serves as an enabling pulse for the charge measurement and sets the time reference for the drift-time measurement.

The process of encoding the drift-time and charge in one double plane can last up to 12.6 μ s in addition to a maximum drift-time of 2 μ s. The electronics

channels of the 16 tubes are mounted on two printed-circuit cards: one contains the analogue circuits; the other one contains scalers and memories required for storing the information of one event for each channel, and the necessary drivers and logic. The cards are mounted on the chamber.

Sixteen chambers, forming two planes, are read out in series by a single CAMAC read-out module; there are 50 read-out modules operating in parallel. Data are transferred into a buffer memory, allowing 256 charge and time measurements (from any 256 tubes) to be stored, or, for showers of average size, 20 to 40 events equally distributed over the detector.

After ageing the electronics for more than 100 h, the failure rate of the cards in use is 5 ± 2 per week, corresponding to a mean time between failures of 26,000 h or a failure probability of 0.02%/1000 h for an integrated circuit. The electronics are accessible, and a faulty card is easily detected, localized, and replaced.

The drift-time as a function of the drift path has been measured using high-energy muons; the result is shown in fig. 10. The average drift velocity is 3.56 cm/ μ s.

The space resolution is limited by the clock frequency of 20 MHz used for the electronics; by the time slewing of the discriminator, which was set at 0.5 ± 0.3 pC; by the diffusion of electrons; and by mechanical tolerances. It has been measured by selecting high-energy muon tracks traversing those parts of the tube layers in the muon spectrometer which are not covered by iron plates to exclude effects of multiple scattering. The deviation observed from the coordinates of a track, determined by the best fit to 10 tubes, is shown in fig. 11; its r.m.s. width of $\sigma = 0.93$ mm is adequate for the spectrometer. It gives an angular resolution of $\Delta\theta_\mu = \pm 2.5$ mrad for muons of 25 GeV/c in the marble calorimeter, and an average momentum resolution of $\Delta p/p = \pm 16\%$ for muons passing through the μ spectrometer.

The relative position of the 13,000 wires has been determined using high-energy muon tracks traversing the detector. The residuals of the measured and fitted coordinates have mean values of less than 0.3 mm.

Figure 12 shows the response of the proportional tubes to hadron showers induced by 17 GeV/c π^- in a calorimeter, with sampling every 10 cm of Fe as in the end calorimeter. We observe a mean pulse-height corresponding to 7.7 equivalent minimum ionizing particles per GeV of kinetic energy and an r.m.s. width of 33.7%. The energy dependence of the response, shown in fig. 13, deviates from linearity at energies larger than 60 GeV, as a consequence of the limited dynamic range of the electronics.

The response is constantly monitored using cosmic-ray muons and is found to be uniform within $\pm 5\%$ over 98 layers of $4 \times 4 \text{ m}^2$ surface area.

2.8 Performance of the calorimeter

Beams of pions and electrons with momenta in the range of 15 to 140 GeV/c have been used to measure the response and the energy resolution of 30 subunits of the calorimeter as well as the angular resolution in the determination of the shower direction. A detailed discussion of the performance of the fine-grain calorimeter will be given in a separate publication [4].

Figure 14 shows the scintillator response, E_{vis} per GeV beam energy, as a function of the incident kinetic energy of pions and electrons. The response of the calorimeter is measured and monitored relative to the most probable energy loss of cosmic-ray muons which satisfy the trigger conditions. The observed ratio of mean energy loss to most probable energy loss for these cosmic-ray muons,

$$\frac{\Delta E_{\mu}(\text{mean})}{\Delta E_{\mu}(\text{peak})} = 1.179 ,$$

with a variance of 0.053, does not vary along the entire calorimeter. We therefore determine $\Delta E_{\mu}(\text{mean})$ from cosmic-ray muons and multiply by the ratio given in eq. (3). This ratio is a function of the muon momentum; however, care is taken to keep the mean muon momentum constant by not changing the trigger condition (see section 5).

The resolution of the energy measurement is well described by a simple dependence on $E^{-1/2}$, as shown in fig. 15; for hadrons we find

$$\frac{\sigma(E_h)}{E_h} = \frac{0.53}{\sqrt{E/\text{GeV}}} , \quad (4)$$

and for electrons

$$\frac{\sigma(E_e)}{E_e} = \frac{0.20}{\sqrt{E/\text{GeV}}} . \quad (5)$$

We note that the hadron energy resolution, $\sim 5\%$ at 100 GeV, is very good for a calorimeter owing to the small sampling step and to the accuracy of the attenuation corrections and the gain calibration of the photomultipliers.

Comparing the lateral profile of showers induced by pions and by electrons, we observe a characteristic difference in width (shown in fig. 16). A selection of events as indicated in fig. 16 allows showers induced by electrons in neutrino-electron scattering to be separated from showers induced by pions in semileptonic neutrino-nucleon scattering. The separation gives a rejection factor of approximately 10^2 , which can be increased to 3×10^2 by a weak cut on the shower length.

Measurements of the spatial distribution of energy deposition in the shower, and of its vertex, can be used to determine the direction of the energy flow of hadron and of electron showers. Figure 17 shows the resolution in the lateral vertex position, obtained from the difference between the shower vertex and the muon vertex in charged-current neutrino interactions. It is well parametrized by the following expression:

$$\sigma_{\text{vertex}} = \left[\frac{19.5}{\sqrt{E/\text{GeV}}} + 0.003 \left(\frac{E_h}{\text{GeV}} \right) \right] \text{ cm} . \quad (6)$$

Fitting a line to the axis of the observed shower profile, we find an r.m.s. resolution of the projected angle of ~ 21 mrad at 100 GeV, and an energy dependence (as shown in fig. 8) which is well described by the following parametrization:

$$\sigma_{\theta} = \left[\frac{0.16}{\sqrt{E/\text{GeV}}} + \frac{0.56}{(E/\text{GeV})} \right] \text{ rad} . \quad (7)$$

The resolution improves by a factor of ~ 2 if the vertex position is known.

The direction of electron showers can be measured with better accuracy because of their narrower profile, as shown in fig. 19.

Presently achieved results on angular resolution may still not represent the limit of the detector performance.

3. THE MUON SPECTROMETER

Forward-going muons produced by neutrino interactions in the target calorimeter are identified and momentum-analysed by a muon spectrometer consisting of four toroidal iron magnets. Each magnet is segmented into iron disks, 5 cm thick in the first module to allow measurement of leaking shower energy, and 15 cm thick in the next three modules, with a total iron length of 3 m, and with proportional drift tubes interspersed between them. The momentum resolution for 80 GeV muons is approximately 25% in the frame magnet and 16% in the forward muon spectrometer.

Figure 20 gives a schematic view of the two different types of toroidal magnets: the end calorimeter and one of the three end magnets. The iron disks have an external diameter of 3.7 m, and a central hole of 16.7 cm diameter to accommodate the coils. They are supported on legs made of stainless steel to minimize leakage of the magnetic flux. The coils consist of 36 turns (18 upwards and 18 downwards) of water-cooled copper tubing. A nominal current of 1000 A thus gives 36 kA turns per module.

The magnetization of the iron has been measured by the induced charge on pick-up coils. Twenty coils were passed through a series of small-diameter holes in the end calorimeter and in one of the end magnets. They were located at azimuthal angles of 0° , 22° , 45° , and 90° , and at five different radii, as shown in fig. 21.

The results of the measurements are shown in fig. 22 as a function of radius and for two azimuthal angles. The magnetic field decreases from 2.1 T at 8 cm radius to 1.6 T at 185 cm radius. Azimuthally, there is a maximum deviation from uniformity of 2%. The mean field strength, averaged over the whole surface, is 1.7 T.

The results for the end calorimeter and for the end magnet agree to within 2%; therefore only one of them is shown in fig. 22. Additional measurements, comparing the field in the first disk (A in fig. 21) and in the central disk (B in fig. 21) of one module, agree to within 3%.

The muon tracks are measured by means of 18 planes of proportional drift tubes (fig. 23); 7 of these planes are interspersed between the iron disks of the end calorimeter, and the other 11 planes between the disks of the three end magnets. Three planes, following the end calorimeter, are rotated around the direction of the neutrino beam at angles of -12.5° , 12.5° , and -12.5° , respectively. Information from these planes allows the matching of tracks reconstructed in two projections for events with more than one muon. All other planes alternate in the horizontal and vertical wire directions.

The chambers in the end calorimeter are of special mechanical design, allowing the entire surface around the central hole to be covered, as shown in fig. 24.

The proportional drift tubes have been described in Section 2. The track coordinates are measured with a precision of approximately 1 mm. Tubes with large pulse heights due to knock-on electrons are not used by the pattern recognition or geometry fit. A geometrical fit is performed using the coordinates of at least five chambers in each projection of the calorimeter and most of the coordinates measured in the muon spectrometer to determine the muon space angles and momentum.

To test this procedure, events with stopping muons have been selected in order to compare the momentum determined by range with that determined by magnetic deflection. Figure 25 shows the difference in units of the standard deviation,

$$R = \frac{p(\text{fit}) - p(\text{range})}{\sqrt{[\Delta p(\text{fit})]^2 + [\Delta p(\text{range})]^2}} = \frac{\Delta p}{\sigma(\Delta p)} . \quad (9)$$

The mean value of R is zero within the experimental uncertainty, thus showing that the two ways of determining the momentum agree; the r.m.s. width of the distribution is 1.04 ± 0.05 , confirming the evaluation of the standard deviation of the momentum measurement.

High-energy muons may lose a considerable amount of energy by radiation when passing through iron. As an example, the probability of a 100 GeV muon radiating at least 10 GeV in passing through 3 m of iron is $\sim 3\%$. Six planes of scintillation counters have been inserted in the gaps of the end magnets to detect and to measure this energy loss. Each plane is composed of 18 scintillation counters, 9 on each side of the central hole (see fig. 26).

Cosmic-ray muons entering the muon spectrometer from the back and stopping in the calorimeter may simulate quasi-elastic scattering of muon-neutrinos by charged-current interaction. To detect and to eliminate such events, the time of flight between the last scintillation counter planes of the calorimeter and of the bremsstrahlung counters is measured and recorded. The difference between the time of flight of a muon leaving the back of the spectrometer and another one entering is ~ 30 ns.

4. USE OF THE CALORIMETER AS A MUON POLARIMETER

The calorimeter structure described before is well suited as a polarimeter for positive muons. It thus offers the possibility to determine the polarization of positive muons, produced in neutrino interactions, that stop inside the calorimeter [9]. For this experimental program the detector of the CDHS Collaboration [2], which precedes this experiment in the CERN neutrino beam line, is used as a target and provides a signature for neutrino events. A schematic view of the two detectors is shown in fig. 27. Positive muons produced in antineutrino interactions are focused towards the polarimeter, and approximately 5% of them stop inside the polarimeter volume. The light, finely subdivided material of the calorimeter allows the detection of the positron from muon decay at rest with an efficiency of 30%.

The track of a muon is recorded by the proportional drift tubes. The last proportional tube plane fired defines where the muon has stopped. This is cross-checked by the sum pulse of all scintillators in one plane. The decay positron is recorded in either the backward (upstream) or the forward (downstream) scintillator plane relative to the longitudinal stopping position. Decay positrons are preferentially emitted in the direction of the muon spin, because of the V-A structure of muon decay. To determine the polarization in a way which is independent of systematic forward-backward asymmetries of the apparatus, the method of spin precession is used. The iron frames surrounding the calorimeter structure are magnetized in a dipole configuration providing a magnetic field of 58 G transverse to the beam direction inside the polarimeter volume. This field was found to be homogeneous to within 2%. The longitudinal component of the spin of a muon at rest precesses with a period of $T = 1.3 \mu s$ in a plane perpendicular to the plates of the polarimeter. It is therefore expected to observe a time-dependent forward-backward asymmetry of positrons parametrized as follows:

$$R(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = R_0 \cos (\omega t + \phi) . \quad (10)$$

The phase ϕ determines the sign of the polarization, whereas the oscillation amplitude R_0 is a product of the muon polarization and the polarimeter analysing power.

Since muons may suffer some depolarization in the stopping material, a comparative study was made between the polarimeter analysing power of 3 cm thick marble plates and 3 cm thick aluminium plates or carbon plates as stopping material. This study was made using polarized positive muons from decays in flight of 140 MeV/c pions at the CERN Synchro-cyclotron. Figure 28 shows the time dependence observed for forward-emitted positrons using marble as a stopping material. The solid line shown in this figure corresponds to a fit to the data parametrized by

$$N_F(t) = N_0 e^{-t/\tau} [1 + a \cdot \cos (\omega t + \phi)] .$$

Values of the oscillation amplitudes as determined by the fit are listed in Table 1 for carbon, aluminium, and marble.

Table 1
Asymmetry in muon decay in different materials

Material	a
C	0.213 ± 0.012
Al	0.215 ± 0.017
Marble	0.204 ± 0.016

These results show that, for positive muons, marble is as good a polarimeter material as carbon and aluminium, materials which are known [10] not to depolarize muons slowing down to rest from several hundred MeV/c. Figure 29 shows results [9] from a precession measurement of leading μ^+ produced by $\bar{\nu}_\mu$ interactions in the CDHS detector [2].

5. THE TRIGGER LOGIC

5.1 Basic trigger structure

The trigger logic uses scintillator information only. From each plane of 20 scintillators in the calorimeter, the following logic signals are available:

- H: at least one counter fired
- D: at least two counters fired
- T: at least three counters fired
- S: at least one of the side counters (for all planes, counters No. 1 and No. 20) fired
- E: energy deposition in the plane greater than a preselected value.

All triggers are built from these plane signals (as shown in fig. 29), requiring certain conditions to be fulfilled in more than one plane. At the level of the whole calorimeter, 20 logic signals are provided (HM, DM, TM, SM, EM, with $M = 1, 2, 3, 4$) requiring a specific plane condition (H, D, T, S, or E) to be satisfied in at least M planes (e.g. T3 means: at least three scintillators have been hit in at least three planes).

All triggers, described in detail below, are based on this pattern information of the scintillator system. They are subject to a minimum threshold of 100 MeV visible energy in the calorimeter. When a condition is required to be fulfilled in a specific plane n , this is noted by a subscript (e.g. D_1 means: in plane 1 at least two hits). A schematic view of the basic trigger structure is shown in fig. 30.

A dead-time of 16 μ s follows every trigger in order to protect the electronics during the conversion time of the ADCs of scintillators and proportional drift tubes.

5.2 The inclusive trigger on neutrino events

In an experiment of this kind, the aim is to trigger as loosely as possible with the available buffer capacity (40 events/spill) and tolerable dead-time losses. The trigger on neutrino events ($H_4\bar{H}_1$) requires a hit in at least four planes (H_4) and no hit in the first plane of the apparatus ($\bar{H}_1$); in this way, incident charged tracks are rejected. This trigger accepts cosmic-ray events at a level of 3500/s. The trigger corresponds to an effective energy threshold of 1 GeV for neutrino-induced showers. Typical trigger rates are 0.2 events/ 10^{13} protons on target in the narrow-band neutrino beam and 10 events/ 10^{13} protons on target in the wide-band neutrino beam. The dead-time is typically 15%.

5.3 Stopping muon trigger

This trigger demands a track entering the front of the calorimeter and not leaving the apparatus at the side or at the end. The trigger is described by $H_2*H_4*\bar{H}_7*\bar{S}1$. In the antineutrino wide-band beam (stopping the leading μ^+) the trigger rate is 1.2 events/burst.

For a μ -stop event the processing differs from the normal type used for all other types of triggers. The events are in fact double events.

i) The early event

The above-described trigger flags the incident stopping muon. This trigger gates the whole event-recording system apart from the ADCs of the scintillators. The trigger opens a gate of 6 μ s to look for late events from muon decay.

ii) The late event

Any H1 trigger within the 6 μ s gate is accepted as a positron candidate. The scintillator ADCs are grouped in sections of four planes. Each late H1 trigger gates the corresponding section, and in this way the energy deposited by the positron candidate is recorded. The scheme allows the acceptance of more than one late trigger. This is essential in order to keep the recording system sensitive to a decay electron even if a noise pulse in a photomultiplier was recorded in any section not corresponding to the longitudinal stopping position of the muon.

5.4 Cosmic muon trigger

Cosmic-ray muons are used to calibrate the pulse-height response of the scintillators and of the proportional tubes. The trigger requires a single track penetrating through at least nine scintillator planes. To achieve such a penetration trigger, the H-signals of every fourth plane (station planes) are combined in a majority logic. At least three such station planes (P3) are required to be hit. The final trigger is $H4 * P3 * \overline{D1}$. The rate of this trigger is 400/s. About seven cosmic-ray events are recorded between the neutrino bursts of the synchrotron.

5.5 Interacting muon trigger

To calibrate the response of the calorimeter to electromagnetic showers, a trigger has been developed to select interacting muons during the neutrino spill. A single track is required to enter the apparatus from the front, deposit some shower energy, and leave the apparatus at the end. For this trigger the total visible energy in the calorimeter must be slightly higher than the energy deposited by a non-interacting minimum ionizing track traversing the whole calorimeter. The trigger used is $H_2 * \overline{D_2} * H_{78} * (E_{vis} > 0.5 \text{ GeV})$.

6. THE ON-LINE SYSTEM

A distributed system consisting of two computers (Hewlett Packard 2100 and 21 MXE) is used to perform the tasks of data acquisition, data reduction, and detector performance monitoring. It can work at a rate of 6 events/s, permitting

the acquisition and transfer to tape of a maximum of 40 neutrino events and of 20 cosmic muon events during the interval of ~ 9.6 s between successive spills of the accelerator.

The information of each event is contained in 3200 ADC channels of the scintillators, in 13,000 ADC and 13,000 TDC channels of the proportional drift tubes, and in a monitoring block consisting of beam information, event bit-pattern, and scaler contents. All information is stored in buffer memories during the spill.

The ADCs of the scintillation counters are equipped with RAM storage for 50 events. The charge and the drift-time of each set of 256 proportional drift tubes is read out in series by a single CAMAC read-out module; there are 48 read-out modules operating in parallel. Only non-zero data are transferred in a handshake mode, at a rate of approximately 2 MHz, into a 256-word-deep buffer memory, thus allowing 256 charge and drift-time measurements from 256 tubes to be stored, corresponding to 30 events of average size. This information, comprising about 4K words, is transferred eventwise between spills in about 10 ms to the on-line computer via a single CAMAC branch highway. The on-line computer performing this task is a Hewlett-Packard 2100 with 32K of 16-bit words memory space.

The scintillator data is checked for consistency and completeness. ADC channels are retained if the bit of the discriminator, set at a pulse height corresponding to $\frac{1}{5}$ the ionization of a minimum ionizing particle, is detected. Every 32 spills, all ADC channels are read out and retained to monitor the pedestals of the ADCs.

A selected sample of events is transferred via a link to the main on-line computer. All events are written on tape; on the average, one 1600 bpi/9-track tape contains 30,000 events.

The main on-line computer is a Hewlett-Packard 21 MXE with 256 kbyte memory and 15 Mbyte magnetic disk memory. Its main task is to monitor the performance of the detector and of the neutrino beam, and to perform sample analysis.

Various histograms are filled during data taking, a run summary is continuously up-dated, and events are written into data buffers on the magnetic disk memory for later display and analysis.

Twenty-five programs, scheduled and steered by a touch-panel display*), can be used to analyse the data and to display histograms. For the proportional drift tubes the most efficient check is made using hit-frequency and drift-count distributions. The ADCs are best controlled by displaying hit-frequency distributions, noisy channels, and channels with varying pedestals. The updated run summary is displayed after each spill. An on-line event display (see fig. 31) is available.

The neutrino beam information is passed directly to a beam monitor program which calculates, updates, and displays the beam width, position, and angle, and the steering of the primary proton beam onto the target.

7. THE DATA ANALYSIS SYSTEM

The off-line analysis of the experimental data is performed by a single program, able to work in a number of different modes, and which is used to make several passes over the data. The program is designed to be flexible and easy to use and to maintain; it is installed on the CDC 7600, IBM 3032, and IBM 370/168 computers at CERN, and on the computers of the collaborating institutions.

It consists of a number of independent processors, called by a set of control routines, which control in an automatic way the flow of data through the processors. The individual processors perform the following functions:

- i) The data are read from tape, decoded, converted from channel counts to energy units using the calibration data, and filtered for cosmic rays.
- ii) A search is made for muon trajectories in the proportional tube planes, first using a combinatorial method to look in the magnet chambers, and then using a track-following technique in the target calorimeter. In order not to confuse the track-finding routines with signals from the shower, the

*) Kinetic Systems, Model 209E.

data points likely to belong to the shower are removed, using an algorithm which takes account of both the pulse height and the hit pattern on a plane [11].

- iii) After subtraction of the energy deposition of any muons found, and correction of the scintillator pulse heights for light attenuation, the region of the detector containing the shower is defined. The barycentre (centre of energy deposition) of the shower is calculated as a combination of the barycentres of the energy seen in the marble target calorimeter and in the iron frames and end system. The shower vertex (interaction point of the neutrino) is calculated using the proportional drift tube and scintillator signals from the first four planes (on each projection) of the shower. The energy flow direction in the shower is defined by the vector joining the vertex to the barycentre. A further estimate of the energy flow direction is made using the barycentre calculated with a lateral weight function, which gives less weight to the (highly fluctuating) lateral edges of the shower. Finally, the shower is classified as electromagnetic or hadronic, mainly on the basis of its lateral width.
- iv) A geometrical fit is made to the points on the tracks found in the magnets, using a least-squares method containing a correction for multiple-scattering and energy-loss effects, as well as for bremsstrahlung where this has been detected. The main problem in this processor is to solve the problem of the ambiguity of the drift-time measurement. A solution based on a parabola fit is used, where the ends of the parabola are well defined by using the last section of the track in the target calorimeter at one end, and by having two measuring planes in each projection at the end of the detector for the other end.
- v) A kinematic fit of charged-current events is made.

Other processors are used to calibrate the proportional tubes and scintillators using specially flagged cosmic-ray data, to align the chamber planes, and to generate a file to display events on a visual display unit.

The program is able to read its own output, which consists, in the case of a physics event, of the input raw data combined optionally with calculated quantities and, in the case of beam monitor information, of a copy of the record, or optionally of records containing accumulated information from several beam monitor records. The data formats are based on a mixture of Hewlett-Packard 16-bit and IBM 32-bit words, easily readable on any computer used by the collaboration.

The data analysis goes through the following steps, where each run occupying one magnetic tape is considered to be an independent entity:

- i) Cosmic-ray data are used to calibrate and monitor the response of the scintillators and the proportional tubes.
- ii) The physics data are filtered for cosmic rays, converted, and written on to a new tape, together with the beam monitor information.
- iii) A physics analysis is made, writing to tape all events and error codes as they occur, together with the calculated quantities and accumulated beam monitor information.

The data summary tapes can be read back by the program for further studies; they are mainly intended for final physics analysis. They can be reduced in volume by rewriting them without the raw data information.

Acknowledgements

We would like to express our gratitude and deep appreciation to our numerous technical collaborators. The successful realization of the detector was only possible thanks to their skill and dedication. In particular we wish to thank W. Albrecht, G. Petrucci, G. Pozzo and U. Ubaldi (magnet design and assembly); G. Basti, R. Donnet, A. King, L. Sokolov and P. Veneroni (design and installation of scintillators and proportional drift tubes); G. Fremont, B. Friend, K. Geske, H. Riege, J. Schütt, Y. Semenov, J.C. Tarlé and H. Verweij (design and installation of electronics for proportional drift tubes); F. Cesaroni, M. Ferrat, S. Guerra, G. Lunadei and A. Tusi (design, construction and installation of ADCs

and photomultiplier electronics); E. Gygi (gas system of the proportional drift tubes); Y. Perrin, E. Rimmer and P. Scharff-Hansen (on-line computing); J. Audier and M. Busi (off-line analysis); W. Coosemans, E. Menant and C. Prodon (survey). Dr. W. Schmidt-Parzefall has contributed to the design of the detector.

REFERENCES

- [1] See, for example, P.C. Bosetti et al., Nucl. Phys. B142 (1978) 1.
- [2] M. Holder et al., CDHS Collaboration, Nucl. Instrum. Methods 148 (1978) 235.
- [3] C. Bosio et al., CHARM Collaboration, Nucl. Instrum. Methods 157 (1978) 35.
- [4] M. Jonker et al., CHARM Collaboration, Performance of the fine-grain calorimeter of the CHARM neutrino detector (to be published).
- [5] V.S. Murzin, Progr. Elementary Particle Cosmic-Ray Phys. 9 (1967) 245.
- [6] B. Friend et al., Nucl. Instrum. Methods 136 (1976) 505.
- [7] M. Ferrat, F. Udo and V. Valente, preprint CERN-EP/79-2.
- [8] B. Friend et al., Electronics for proportional drift tubes, CERN Yellow Report, in preparation.
- [9] M. Jonker et al., CHARM Collaboration, Phys. Lett. 86B (1979) 229.
- [10] See, for example, R.A. Swanson, Phys. Rev. 112 (1958) 580.
- [11] K.H. Mess, M. Metcalf, R.S. Orr, B. Kröger and A. Rosanov, Track-finding in a fine-grained calorimeter, CERN DD/80-7 (1980).

Figure captions

- Fig. 1 : Partial view of the fine-grain calorimeter and the muon spectrometer. Each subunit is composed of a marble plate of $3 \times 3 \text{ m}^2$ surface area and 8 cm thickness, a layer of 20 scintillators 15 cm wide and 3 m long, and a layer of 128 proportional drift tubes 3 cm wide and 4 m long. The calorimeter is surrounded by a frame of magnetized steel and followed by four toroidal iron magnets of 3.7 m diameter, each 75 cm thick.
- Fig. 2 : Detail of the disposition of the 12 pick-up coils, L1-L3, T1-T3, R1-R3, B1-B3, for magnetic field measurements on the steel frame surrounding the calorimeter.
- Fig. 3 : Pulse-height distribution recorded for cosmic-ray muons crossing a scintillation counter at the centre normally to the scintillator plane.
- Fig. 4 : Response of a scintillation counter as a function of the distance measured from its light-guide. The response curve corresponds to an attenuation length of $\lambda = 3.9 \text{ m}$. A fitted parametrization of the response according to eq. (2) is shown as well.
- Fig. 5 : Distribution, in September 1978, of attenuation length in the sample of 1600 scintillation counters (see, however, the remark in Section 2.4).
- Fig. 6 : Mean deviation of the measured attenuation from the calculated value used for correcting.
- Fig. 7 : Distribution of the product pM sensitivity $\times$ gain of 600 photomultipliers after adjustment of the high voltage using series resistors.
- Fig. 8 : Scheme of the electronics used to process pulses of the photomultipliers. The signals are split for pulse-height measurements in two 8-bit ADCs and for digital analysis.

- Fig. 9 : Circuit used to drive a twisted-pair cable symmetrically by the output pulses of the anode and the last dynode of the photomultipliers.
- Fig. 10 : Relation of drift time and drift path of the proportional drift tubes. The average drift velocity is 3.56 cm/ μ s.
- Fig. 11 : Observed deviation from muon tracks measured by the proportional drift tubes. The standard deviation is $\sigma = 0.93$ mm, mostly due to the clock frequency of 20 MHz and to the time slewing of the discriminators.
- Fig. 12 : Response of the proportional tubes to 17 GeV/c pions in units of the corresponding number of minimum ionizing particles. The r.m.s. resolution is 33.7%.
- Fig. 13 : Response of the proportional tubes of the calorimeter to pions of different energies. Above 50 GeV the response deviates from linearity because of the limited dynamic range of the electronics.
- Fig. 14 : Response of the scintillation counters of the fine-grain calorimeter to beams of electrons and pions. The error bars indicate the estimated systematic uncertainties.
- Fig. 15 : Energy resolution of the fine-grain calorimeter for pion beams of energy between 15 and 140 GeV. The line is a parametrization, $\sigma(E_h)/E_h = 0.53/\sqrt{E/\text{GeV}}$.
- Fig. 16 : a) Distributions of the difference ΔW between the observed width of pion and electron showers and that expected for a hadron shower as measured by the scintillators in beams of 6, 15, and 50 GeV/c. The arrow indicates the cut at $\Delta W = -6$ cm used to separate pions and electrons.
- b) Distributions of the normalized r.m.s. width of the energy detected by the proportional tubes in beams of 15 and 50 GeV. The arrow indicates the cut at $\sigma = 9$ cm used to separate pions and electrons.

- Fig. 17 : Shower vertex resolution measured using the difference from the muon vertex in charged-current neutrino reactions as a function of shower energy. The parametrization shown is given in eq. (6).
- Fig. 18 : Resolution of hadron shower direction measurement in one projection as a function of shower energy. At 100 GeV the r.m.s. resolution is 21 mrad.
- Fig. 19 : Resolution of electron shower direction measurement in one projection as a function of electron energy. At 15 GeV the r.m.s. resolution is (12.5 ± 1.0) mrad.
- Fig. 20 : a) Front, side, and top view of the end calorimeter composed of 15 iron disks, each 3.7 m in diameter and 5 cm thick. A central hole accommodates two coils, one upwards and one downwards, creating a toroidal field of 1.7 T average strength. The iron disks are interspersed with proportional drift tubes to measure shower energy leaking out of the fine-grain calorimeter.
- b) One of the three end magnets forming, together with the end calorimeter, the forward muon spectrometers. It is segmented into five iron disks of 15 cm thickness each, and magnetized to 1.7 T. The legs are made of stainless steel to minimize the leakage of the magnetic flux.
- Fig. 21 : Azimuthal (0° , 22.5° , 45° , 90°) and radial positions of pick-up coils for magnetic field measurements of one end magnet. Both the front plate (A) and the central plate (B) have been measured.
- Fig. 22 : Radial dependence of the toroidal magnetic field of one module of the forward muon spectrometer; the maximum azimuthal asymmetry is 2%.

- Fig. 23 : Schematic view of the layout of proportional drift-tube planes sampling tracks in the muon spectrometer. Seven planes are interspersed between the iron disks of the end calorimeter, the end magnets are equipped with eleven planes. Planes with horizontal wires are marked H, with vertical wires V. The chambers are shifted laterally by one-half wire distance with respect to each other, by a positive (P) amount or by a negative (N) amount. The three planes following the end calorimeter (V' , H' , $-V'$) are rotated around the direction of the beam at angles of -12.5° , 12.5° , and -12.5° , respectively, to allow track matching in space for multi-muon events.
- Fig. 24 : Layout of the special proportional drift chambers covering the iron disks of the end calorimeter.
- Fig. 25 : Observed difference of momentum determined by range and by magnetic deflection in units of the standard deviation, $R_0 = p(\text{fit}) - p(\text{range}) / \sigma(\Delta p)$. The mean value of R is consistent with zero, the standard deviation of the R values is ~ 1 , as expected.
- Fig. 26 : Disposition of one of six planes of scintillation counters interspersed between the end magnets of the muon spectrometer to detect and measure muon energy loss by bremsstrahlung.
- Fig. 27 : Layout of the polarization experiment. The target consists of 19 magnetized iron modules (Ref. 2) and layers of drift chambers and scintillation counters interspersed, providing muon tracking and calorimetric measurements, respectively. Positive muons are focused towards the polarimeter.
- Fig. 28 : Observed rate of forward-decaying positive muons in a geometry similar to that of the fine-grain calorimeter.
- Fig. 29 : Time dependence of observed relative backward-forward positron asymmetry from decays of μ^+ produced in high-energy antineutrino interactions.

Fig. 30 : Trigger logic showing the pattern trigger provided by combining the majority logic information derived from each of the subunits of the calorimeter: $H(\geq 1 \text{ hit})$, $D(\geq 2 \text{ hits})$, $T(\geq 3 \text{ hits})$, S (at least one of the side counters 1 or 20 hit). This information is strobed with a minimum energy deposition requirement, E_{TOT} , derived from the sum of all scintillator planes.

Fig. 31 : On-line event display showing scintillator and drift-tube information of a charged-current neutrino event in a side view.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20 a)

Fig. 20 b)

Fig. 21

Fig. 22

Fig. 24

Fig. 25

BREMSSTRAHLUNGS COUNTERS

Fig. 26

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31