THE VERTEX AND LARGE ANGLE DETECTORS OF A SPECTROMETER SYSTEM
FOR HIGH ENERGY MUON PHYSICS

The European Muon Collaboration

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Abstract

A description is given of the detector system which forms the Large Angle Spectrometer and Vertex Detector of the EMC Spectrometer. The apparatus is used in the NA9 experiment which studies the complete hadronic final state from the interaction of high energy muons.

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1. Introduction

Deep inelastic muon scattering has been extensively studied during recent years by several experiments. The main emphasis has been given to measurements of the deep inelastic structure functions F_2 for proton, neutron and heavy nuclear targets as a function of x and Q^2 , studies of multimMuon production which give information on vector meson and charmed meson production, and also the measurement of hadron production at forward cms angles. The European Muon Collaboration (EMC) has contributed in large measure to this research program during 1979 and 1980 using the forward magnetic spectrometer described in [1]. The apparatus described in this paper has been built to detect hadrons in the central and in the target fragmentation regions. Together with the forward spectrometer complete hadronic final states may be studied (an original aim of the EMC [2]). With such complete coverage, investigations may be made of topics such as parton (quark, gluon, diquark) fragmentation, multiple jet production and the production of strange or charmed quark jets.

Such aims can only be achieved by constructing a dedicated vertex detector [3] which is sensitive close to the interaction point and gives geometric and kinematic information about all tracks. These requirements are satisfied by a streamer chamber located in a magnetic field. In order to obtain the masses of the particles involved a set of Cerenkov counter and Time of Flight hodoscopes is necessary. Finally, in order to improve the momentum resolution for tracks, a large lever arm can be employed by inserting track position detectors in the large angle region, but at some distance from the vertex.

This report describes those pieces of apparatus which were added to the forward spectrometer system and which constitute the Vertex and Large Angle Spectrometer used for the NA9 experiment at the CERN SPS.

2. General Features of the Large Angle Spectrometer

In the NA9 experiment the muon detection is the same as for the earlier NA2 experiment. No details are given for the forward spectrometer detectors.

Briefly the incident muon is measured by hodoscopes (BHA, B) in the beam (see fig. 1), the scattered muon is measured in drift chambers (W1-5) located before and after a conventional magnet (FSM). Proportional chambers in the magnet gap constrain the trajectory in the magnetic field. Muon identification uses an iron hadron absorber in conjunction with further drift chambers (W6,7) which measure only muon tracks. A trigger for the system is obtained using the hodoscopes H1-4. It imposes on the scattered muon a minimum momentum (~ 15 GeV) and a minimum angle ($> 0.5^\circ$). A halo wall minimises together with target pointing of the main trigger the number of false triggers. Since the mass of the target for the NA9 experiment is less than for NA2 (ratio 1:6), the importance of the halo veto system is increased.

The acceptance of the forward spectrometer hadrons is limited to forward cms angles, i.e. with $x_{\text{Feynman}} \geq 0$. In order to cover the whole x_F range of produced hadrons the hydrogen/deuterium target has been surrounded by a large streamer chamber. The triggerable character of this visual apparatus which has a memory time only of the order of 1 μsec , minimises the background from old beam tracks (~ 10 'old' muons per picture). Further, the good track separation properties and precision in track measurement make the streamer chamber a vertex detector well suited to this particular experimental physics.

To provide good momentum determination for tracks with momenta up to 20 GeV the streamer chamber is located in a large superconducting magnet (VSM) which has a $\int B d\ell \sim 4$ Tesla Metres bending power.

Identification of particles is achieved by using four kinds of threshold Cerenkov counters C0, C1, C2, CA covering different ranges of momentum space. In the forward direction, where most particles have momenta greater than 5 GeV, the combined C0-C1-C2 gas Cerenkov counters give an almost complete separation of $\pi/K/p$ from 2.5 GeV to 80 GeV. On the other hand for angles > 10 degrees the momenta are comparatively low and identification is achieved using the wide angle part of C0 in conjunction with the aerogel Cerenkov Counter CA. In the large angle region the identification information is completed by the Time of Flight hodoscopes F1, F2, F3 and F4. The arrangement of the detectors in the set-up is shown in fig. 1.

To ensure the link between the streamer chamber and external detectors, to improve the precision for the tracks measured in the streamer chamber using the increased lever arm and to aid pattern recognition, three position detectors are added to the spectrometer. The first consists of a proportional wire chamber system PV1,2,3 located inside the vertex magnet gap and covering the complete aperture ($\pm 60^\circ$) in the horizontal plane. The second is a small proportional chamber POC which, together with the existing POA and POB, works satisfactorily in the high rate region of the beam where the larger chambers are insensitive. The third of these detectors is a system of drift tubes WV1,2,3,4 located some 4 metres from the VSM. WV1 and 2 cover the region 10° - 30° in the horizontal plane which is just outside the aperture of the forward spectrometer magnet. Similarly WV3 and 4 extend the coverage of the forward spectrometer in the vertical plane to match the aperture of the VSM.

This system of detectors ensures that low angle moderate momenta tracks, which are difficult to measure within the streamer chamber but which don't enter the FSM magnet, are measured satisfactorily. The rôle and the importance of the various detectors is indicated in Table 1 which lists some general parameters calculated using the Feynman-Field model for hadron production.

Finally, although certain aspects of the forward spectrometer system had to be modified to take account of the two magnet system (e.g. trigger configuration), the NA9 experiment benefited greatly from the experience with the NA2 running. The data acquisition system is a straightforward extension of that used for NA2 [4] and is such that new detectors could be commissioned and tested with minimal interference to that part of the system which was already working. In an experimental set-up with 19 different kinds of apparatus this is a significant consideration.

The trigger, as for NA2, is constructed from the hodoscope signals using electronic matrices [5] so as to request the trigger particle to point back to the target in both y and z projections (fig. 1) make a minimum scattering angle of $\sim 0.5^\circ$ and to be a muon. The latter is implied by the hits in hodoscopes H3 and H4 which are downstream of the hadron absorber. Such a trigger was found to contain contributions which amounted to $\geq 60\%$ from low

Q^2 electromagnetic events, high multiplicity events in which no muon was observed and other backgrounds. The observed trigger rate in NA2 with a 6m H_2 target was $\sim 5 * 10^{-6}$ per incident beam muon. The contribution of large angle halo muons was found to be relatively small. In NA9, with a 1 m H_2 target the equivalent trigger rate shows a very substantial reduction to $4-5 * 10^{-7}$ per incident muon. The operation of the veto system is correspondingly more important, nevertheless $\sim 25\%$ of the triggers observed are found to be large angle halo which (since there is no beam requirement in the hardware trigger) can perfectly simulate a muon scatter by passing through the beam hole in the vertex system.

3. Description of the Apparatus

3.1 The Streamer Chamber

The streamer chamber has a three gap system with two high voltage electrodes, one for each polarity, thus avoiding an electrode in the median plane where the particle density is the highest. The free space between the high voltage electrodes allows a liquid hydrogen (deuterium) target to be inserted. The streamers developed along the tracks are viewed by three cameras equipped with image intensifiers; the latter permit a lower operating voltage of the chamber which results in smaller light points and a more isotropic behaviour.

3.1.1 Chamber

The chamber is a rectangular box (see fig. 2) $200 \times 120 \times 72 \text{ cm}^3$; the box is divided vertically into three gaps (18, 36 and 18 cm) by horizontal electrodes of phosphor-bronze grids which give 80% light transmission. The grids are stretched on support frames attached to the sidewalls of the chamber. The sidewalls of the chamber are of 50 mm thick Rohacell coated on each side with 1 mm Lexan. The gas volume is closed by a mylar foil (120 μm) with good optical quality. All outside electrodes are at ground potential and the whole system is completely closed to provide a good radio-frequency shielding.

The gas mixture is Neon-Helium (70% Ne, 30% He) with a 0.3% admixture of isobutane which reduces the high voltage required by 12%. The memory time, 1-1,5 μ sec of the chamber is controlled by the addition of a few times 1/10 ppm of the gas SF_6 . The memory time is monitored using a separate ionization chamber [6].

The high voltage (± 350 kV) for the chamber is obtained using a Marx generator with 21 stages for each polarity. The capacitance of each stage (8 ceramic capacitors) is 22 nF and is charged up to 19 kV. The first stage common to both columns is triggered by a 10 kV pulse. The charging time is 150 msec but a further dead time of ~ 50 msec is imposed after each pulse to reduce afterparking.

The pulses are shaped in a double Blumlein which reduces the 100 nsec output pulses from the Marx generator to ~ 10 nsec. The spark gap, positioned between the inner electrodes of each polarity, has a 16 mm gap between the electrodes and is operated at 5.0-5.5 bars SF_6 . The pulse height jitter observed is ~ 1.5 -2.0%. The high voltage pulses are driven to the chamber through an adaptor which matches the impedance (21 Ω) of the chamber and are absorbed after the chamber to avoid reflections.

The time for generation of the high voltage pulse is ~ 500 nsec, therefore it is necessary to introduce an additional delay (200 ns) to the trigger (500 ns) to avoid r.f. effects for the pulse in the other electronic detectors in the experiment.

3.1.2 Target

The hydrogen target assembly is constructed entirely from non conductive materials. The liquid hydrogen is contained in a 100 cm long, 7 cm diameter tube oriented on the beam axis and located inside the sensitive volume of the streamer chamber (see fig. 2). This target cell is constructed of mylar foil (250 μ m thick) covered with thirty layers of 6 μ m mylar foil which provide thermal insulation. The whole is enclosed in a further tube which has two walls of 9.5 cm and 11.0 cm diameter made of 2 mm and 1 mm thick Dallite respectively. The vacuum is maintained between the target cell and the inner

surface of this double tube. The space between the two layers of this outer tube is used for ventilation and leak detection.

The total thickness of the target walls is 0.0029 of an absorption length for particles exiting the end of the target, less than 55 mm from the axis; for larger radii it becomes $0.0034/\sin\theta$ of an absorption length, with θ being the angle of the track with respect to the beam axis.

It is also planned to use a high pressure (20 bars) gas target of the same size as the hydrogen target but contained in a mylar cylinder reinforced by Kevlar fibres and having a total wall thickness less than 1 mm.

3.1.3 Optical system

The optical system consists of the cameras, the lens together with the image intensifier and the fiducial system used in the calibration procedure. The optical system determines the quality parameters of the pictures (resolution, separation) and the input calibration parameters for track reconstruction (optical definition, distortion parameters). The mounting is illustrated in fig. 2.

The three cameras view the sensitive volume with different stereo angles (15° between cameras I and III, 12° between II and I/III) and the optical axes are tilted towards the streamer chamber centre. The film transport is performed by a vacuum capstan which can operate with a maximum repetition rate of 10 pictures/second. Image intensifiers are used to minimise the necessary streamer length. They are electrostatic focussing single stage tubes (Varo, type 1248-3 with P11 phosphor) with diameter 4 cm and a light gain of ~ 100 . The film is directly pressed on the fibre optic output window by a soft membrane. The image intensifiers have a resolution of 55 line pairs per mm and they use 15 kV DC. The magnetic field of ~ 200 -300 Gauss at the position of the image intensifiers necessitates shielding with Permanorm tubes in order to reduce the effective field to 2-3 Gauss. The residual effect is accounted for along with the other optical distortions.

The optical lens (Nikon-Rokkor type; 58 mm/1.4) located 384 cm from the streamer chamber centre give a demagnification factor of 66. An aperture 2.0-2.8 permits a good depth of field. The overall resolving power of 34 lines per mm on film (Kodak 2498) corresponds to a theoretical track separation of 2.5 mm in space.

The fiducial system consists of a set of marks at the bottom of the streamer chamber which provide picture to picture adjustment and of a grid at the top of the chamber which allow the determination of distortions. Both are mechanically independent of the streamer chamber body. The fiducial marks at the bottom are illuminated crosses, etched on a thin lucite disc and supported by a glass fibre epoxy plate; their position is known to within 200 μm in space. The upper grid is made of 36 nylon wires stretched with 200 g tension in two orthogonal directions on Invar rods with a precision of 20 μm . The pitch is 10 cm such that the whole grid has a coverage of 200 x 200 cm^2 . The 600 μm thick nylon wires are treated with a fluorescent paint and for picture taking are illuminated uniformly by a UV lamp. Four of the 36 wires have been measured in position with respect to the general coordinate system at three points with an accuracy of ~ 200 μm in space. Given the mechanical precision of the system and the absolute position of the fiducials, the various parameters and distortions of the optical system are then determined. Data taken with zero magnetic field, and consequently straight particle tracks, are used to link the streamer chamber system to that of the downstream electronics detectors and further provide a check on the optical system under running conditions.

3.2 The Vertex Magnet

The vertex spectrometer magnet (VSM) is a superconducting dipole magnet with a circular pole geometry. The poles have a diameter of 2 m and a vertical separation of 1 m. The iron return flux yoke is asymmetric to allow a large aperture of $\pm 60^\circ$ in the forward horizontal angle (y-coordinate) and of $\pm 10^\circ$ in the vertical angle (z-coordinate) from the centre of the magnet as indicated in fig. 1. The maximum current of 5000 A gives a field of 1.5 T within a large volume. The superconducting state is maintained by a forced flow of Helium. The associated refrigerator has a cryogenic power of 400 W for a total power consumption of 250 kW.

The open configuration of the return yoke leads to a field which is largely uniform in the central region, but which is strongly inhomogeneous at the edges. The field was mapped with 3 nominal excitations corresponding to various standard beam energies foreseen. The fringe field region was also mapped outside the magnet up to 6 m along the beam, 6.1 m transverse to the beam (y) and 2.2 m vertically. The measurements were performed in situ with the forward spectrometer magnet (FSM) also operating so that the superimposition of the two fields in the intermediate region was properly accounted for, although in practice this produced a negligible effect.

The mapping with movable hall probes used cell sizes of 6 cm in x, 6 cm in y and 5 cm in z and three combinations of VSM/FSM currents were used (5000/5000 A, 4100/4000 A, 1745/2000 A). The presence of a downstream experiment meant that the muon beam should emerge from the two magnets undeviated from its original path; hence equal and opposite field integrals were required for the FSM and VSM. In such a configuration the charged particles emerging from the target are focussed at the position of the absorber and there is a tendency to concentrate high momentum hadrons in the central regions of the chambers W45.

The field map analysis was made in three overlapping zones to improve the parameterisation, this latter was a representation in cylindrical coordinates. The mean error is of the order of 10 Gauss for the main (z) component, but is larger near the coils. By imposing the symmetry given by the mechanical design the calculated field is within 2 Gauss of the measured values on the surface of the boxes.

3.3 Position Measurement Devices

3.3.1 Proportional Vertex Chambers PV1,2,3

There are three proportional chambers PV1,2,3 mounted in the exit aperture of the VSM as shown in fig. 1. The side supports of fibre glass FE27 are made as thin as possible to minimise the material in the aperture. The sensitive area of PV2, the central chamber, is $280 \times 100 \text{ cm}^2$ and of PV1 and PV3 $130 \times 80 \text{ cm}^2$.

Each chamber contains six planes of anode wires, two vertical, two inclined at $\pm 45^\circ$ and two at $\pm 18^\circ$. The signal wires are of 20 μm gold plated tungsten with a separation of 2 mm. In PV1 and PV3 the signal wires are internally connected in pairs to give an effective pitch of 4 mm. The cathode planes are made of panels of 10 ± 0.2 mm thick Rohacell 31 foam covered on each side with a 75 μm mylar foil glued with Araldite. The mylar foils are in turn coated with a spray of graphite ~ 75 μm thick. This cathode construction allows the anode wire tension to be supported with a minimal outer frame combined with an acceptable mass of material in the sensitive region. The beam passes through the centre of PV2 and this region is deadened as explained in [7].

The readout is from either top or bottom of the chambers. The amplifier discriminators, sixteen per card, are mounted in crates near the chambers and the balanced ECL output pulses are transmitted on twisted pair cable (32 pairs per cable) to the counting room. The receiver modules contain 720 nsec delays (surface acoustic wave devices) and perform latching and control logic operations. They are mounted in standard RMH crates for control and system encoding.

Test beam results and experience in the experiment show that a long plateau of 400 volts is obtained above 5.1 kV and a delay curve with sharp rise and fall allows a gate width of 50 nsec to be used. The gas mixture is Argon (70%), Isobutane (24%), Freon (0.8%) and Methylal (4%).

The chamber and electronics system are checked on-line during data taking using both a test pulse system and an efficiency determination based on real data. For PV2 the obtained r.m.s. point reconstruction is 0.5 mm (1.2 mm) in the horizontal (vertical) direction; the track separation in term of distance between points is 4 mm (12 mm) in the same axis. With these intrinsic characteristics, not taking into account the plane efficiencies and without using any external information on track positions, a Monte Carlo study predicts 94% of good reconstructed tracks and 4% of ghost tracks.

3.3.2 Vertex Drift Tubes WV1,2,3,4

One reason to choose drift tubes rather than drift chambers is that drift tube arrays can be built as self supporting structures, thus reducing the size of the frames and minimising the dead spaces between them and any adjacent detector [8]. WV1 and WV2 are mounted as close as possible to either side of the Cerenkov counter C1 while WV3 and WV4 extend the vertical acceptance of the forward spectrometer system above and below the W1 drift chamber (fig. 1).

The large detectors WV1 and WV2 consist of 11 layers of 36 tubes (6 with vertical tubes, 5 with horizontal) covering an area of $200 \times 200 \text{ cm}^2$; each of WV3 and WV4 consists of 7 layers (4 with 20 horizontal tubes and 3 with 36 vertical) covering an area of $200 \times 50 \text{ cm}^2$. In addition ambiguities are resolved with a rough measurement of spatial points by determining the longitudinal coordinates along the tubes of the two outer planes (of each module) with external delay lines.

The cylindrical tubes have a 5 cm inner diameter and are made of 1 mm thick bakelite paper. The internal surface is coated with carbon black (graphite diluted with water and glue) in order to give a moderately resistive cathode (about $100 \text{ k}\Omega$) to prevent "cross-talk" between tubes. Alternatively a highly resistive cathode (more than $1 \text{ M}\Omega$) is used for those tubes (the outer plane ones) that have to induce coupled signals on the external delay lines. The sense wire in the centre of each tube is made of $20 \text{ }\mu\text{m}$ gold plated tungsten.

Tubes are supported at their ends by 2 cm thick aluminium flanges and in the middle by a 3 mm thick central flange to reduce mechanical sagging to less than 1 mm. Such a structure, with 5.2 cm diameter holes bored with high precision, ensures the positioning of the wires at both ends within $100 \text{ }\mu\text{m}$. The left-right ambiguity is solved by staggering successive planes of the same orientation such that the tube centres, seen from the side, fall on a circle (of $\sim 2 \text{ m}$ radius); this kind of staggering is also a good solution to minimize the number of dead areas (tube walls) crossed by a particle.

The printed delay lines are glued to $200 \times 100 \text{ cm}^2$ foam panels 2 cm thick which are located directly against the outer planes of tubes. Each

delay line picks up from 2 tubes and is 200 cm long with readout at each end. Its electrical features are a characteristic impedance of 80Ω and an inverse propagation speed of 2.55 nsec/cm giving a maximum delay of 510 nsec.

The choice of gas is related to the tolerable non-linearity in the space-time relationship generated by the strongly inhomogeneous electrical field ($1/r$ type). The best compromise is found to be 80% Argon 20% Ethane, which gives a maximum drift time of 580 nsec for 2.5 cm drift distance (the average drift velocity is 4.3 cm/ μ sec) at an operating voltage of 2.1 kV. Care has to be taken that gas impurities (eg. from outgassing of the walls and permeability of the tubes) be minimized because they lead to strong distortions of the space-time relationship near the tube walls where the electrical field is low. The detectors WV1, WV2 and WV3-4 each have an independent gas recycling system with built-in water filtering operating at a flow rate of 150 l/minute for the total volume of 1.6 m³. The gas purity is monitored by comparing the signals induced by a high intensity Sr⁹⁰ source in two small drift chambers, one receiving the original gas mixture and the other circulating through the tubes. With this system it is possible to detect a variation of 0.5% in the drift velocity with respect to the reference value.

The electronics for the drift tube signals and for the delay lines are identical apart from a pre-amplification and inversion stage on delay lines. Amplifier discriminators (CERN type 4241) are mounted close to the tube ends and modified cards close to the delay line ends. They feed the signals through twisted pair cables to the drift time recorders (DTR, CERN type 247) which measure the time with about 5 ns resolution. Test pulses from the amplifiers are used to monitor the DTR modules and Romulus readout system.

By optimizing a specific space-time relationship for each of the modules WV1,2,3,4 and for each ten day running period, a spatial resolution of 180 μ m (r.m.s.) is obtained. Using an average and unique relationship for simplicity gives a result between 250 and 300 μ m depending on the stability of the gas system. The comparatively large signal width on the sense wires prevents multihit detection in a tube, thus causing some inefficiencies. However the track density in this part of the large angle detector is low

enough so as not to cause a serious problem (see Table I). Measurements made under realistic beam conditions show an efficiency smoothly decreasing from almost 100% (up to 7 mm from the sense wire) to 92% near the walls, a track being defined within a road width of ± 1.5 mm; the inefficiency can be explained by δ -ray emission and absence of multihit detection. The integrated efficiency of a single tube is 97% and that of a full plane of 36 tubes is 93%, the difference being due to the dead regions of the tube walls. For the delay lines the efficiency is greater than 95% and the resolution is 6.5 mm (r.m.s.) combining both ends. This is clearly sufficient to resolve ambiguities, the distance between two wires being 53 mm.

3.3.3 Additional Beam Chamber POC

The proportional chamber POC, placed between the chamber PV2 and the C0 Cerenkov counter (fig. 1), is used to give position and angle of tracks in the beam region where PV2 is made insensitive. POC has an octagonal sensitive area such that its minimum diameter is 15 cm. It is designed to work in particle fluxes up to 10^8 μ /sec and it is composed of eight planes, two planes for each of four wire orientations which place sense wires at 0° , 60° , 90° and 120° to the horizontal axis perpendicular to the beam. For each orientation the two planes have sense wires displaced by 0.5 mm, one with respect to the other, giving an effective wire spacing one half of the mechanical pitch (1 mm).

The construction techniques are those used for the construction of POA and POB as described in [1]. The gas system and electronics are common with the PV chambers.

3.4 Particle Identification

3.4.1 Cerenkov Counter C0

The threshold gas Cerenkov counter C0 located close to the VSM is designed to identify particles of as low momentum as possible, to cover the maximum acceptance with good spatial resolution and to do this in the minimum depth and with the minimum material.

The gas chosen to satisfy as far as possible these conditions is neopentane (C_5H_{12}) which has a refractive index $n-1 = 171 \times 10^{-5}$ at 436 nm and STP. The nominal momentum values at threshold are 2.4, 8.4 and 16.0 GeV/c for π , K and p respectively and the theoretical photo-electron number is $N_{\infty} = 26$ with an expected value for the Cerenkov parameter N_0 of 105 from test measurements with Freon 114. A disadvantage of neopentane is that it is heavier than air and that a concentration of 1.4 - 7.5% in air is flammable. The condensation point is 9.5° C at STP and so there is also a risk of implosion; these considerations imply the use of a sophisticated and reliable safety system.

Designed as a single tank, the CO detector has an overall volume of about 7 m^3 (see Table II). It is constructed with twelve cells, each covering 11° horizontally and 10° vertically and arranged symmetrically with respect to the beam as shown in figs 1 and 3. The radiator length from input window to the back mirror varies from 80 to 98 cm. The light produced by particles in the beam region is screened by a 12 cm diameter tube. The front and back double foil windows are filled with halon (Freon 13B1) and there is a rapid exhaust system ($1.5 \text{ m}^3/\text{minute}$) which allows the detector volume to be quickly purged. The gas system is a closed circuit with a liquid compression system. In the case of a large internal pressure drop, automatic N_2 filling is implemented. The gas system controls the pressure (10 ± 2 mm water above atmosphere) and the temperature (25°C). These are all continuously recorded, checked and regulated. The temperature control is effected by a water heating/cooling system mechanically integrated into the top and bottom walls of the CO tank; during filling and running of CO the refractive index is checked by an acoustic resonator.

The Cerenkov light reaches the photomultipliers via two mirror reflections and light funnels (fig. 3). The first reflective plane consists of spherical mirrors ($R = 1.15 \text{ m}$) on the back of the detector, each covering a $75 \times 75 \text{ cm}^2$ surface, made of a sandwich of aluminized mylar foil and Nomex honeycomb (10 mm thick) and glass fibre tissue. The twelve secondary spherical mirrors ($R = 0.7 \text{ m}$) each with $55 \times 65 \text{ cm}^2$ area are made of a 1.3 cm sandwich of aluminized plexiglass, Nomex honeycomb and glass fibre tissue. The reflectivity of all mirrors is greater than 80% at 220 nm wavelength. The light funnels associated with each photomultiplier have a

quadratic shape at the entrance, to fit into a 4x4 matrix cell, becoming a Hinterberger-Winston [9] cone at the photomultiplier. A 2 mm thick fused silica window glued on the funnel end separates the gas volume from the outside. The optical arrangement designed to handle the expected particle density (see Table I) has 8 matrices of 4 x 4 funnels ($10 \times 10 \text{ cm}^2$) to cover the central region and 4 matrices of 2 x 2 funnels ($20 \times 20 \text{ cm}^2$) to cover the outer region. Given this granularity, two particles are expected to enter a single cell in a maximum of 18% of the cases.

The photomultipliers used are 2 inch diameter in the central region and 5 inch in the outer region matching the funnel sizes. Both types of tube are operated with a high first dynode potential which is stabilised with zener diodes. At the tube position the fringe field of the VSM has values of ~ 100 Gauss. The transverse field components are shielded passively with a 1.5 mm thick μ -metal cylinder and a 6 mm thick low carbon steel tube housing the photomultiplier and in addition a 5 mm thick low carbon steel shielding round the light funnel matrices. The longitudinal field component is counteracted with compensating coils wound around each matrix of tubes. The ampère-turns in each of these 12 coils is adjusted in order to operate each tube in the plateau of the photomultiplier gain.

The anode signals of the tubes are fed to high impedance discriminators to give stop signals for the TDC's [10] set with 50 psec/channel. The pulse heights for each channel are recorded by ADC's [10]. The detector operation is monitored on-line, the pedestals are measured and the high voltage and gains are checked so that a nominal calibration of 10 ± 1 ADC channels/photo-electron is maintained. This check is made using a fit to the LED generated spectra; LED's are arranged in front of each mirror and light funnel to allow control of long term reflectivity variation.

3.4.2 Cerenkov Counter C1

The threshold gas Cerenkov counter C1 is designed to provide identification of particles intermediate in momentum between those identified in C0 at lower momentum and C2 at higher momentum. Filled with purified nitrogen ($< 100 \text{ ppm O}_2$) at atmospheric pressure $(n-1) = 28.2 \times 10^{-5}$ at

20°C) it gives a threshold for π , K and p of 5.6, 20 and 38 GeV/c respectively.

The size of C1 is determined vertically by the aperture of the VSM and horizontally by that of the FSM and subtends angles of $\pm \sim 10^\circ$ horizontally and vertically at the target (see fig. 1). The entrance window is $108.6 \times 143.3 \text{ cm}^2$ and the exit window is $166.8 \times 204.4 \text{ cm}^2$; main parameters of the counter are given in Table II. The overall length is 187.5 cm and the effective radiator length varies from 131.3 cm to 170.0 cm giving an expected plateau yield of 8 photo-electrons.

The light but rigid body of the Cerenkov counter is constructed of aluminium and each of the windows has two foils of 100 μm mylar and 30 μm Tedlar. A blackened tube with 12 cm diameter is fitted around the beam region to screen off the light from the muon beam particles.

The back mirror gives images of the target and the phototubes, and is divided into 64 spherical elements with radii of 190, 210 and 230 cm depending on their distance from the focal plane. The mirrors are made of 0.4 mm glass which is pressed and glued onto preshaped Rohacell forms; the size of each mirror is $26.5 \times 20.0 \text{ cm}^2$. They are coated with aluminium and magnesium fluoride (MgF_2) and have a reflectivity of 89.5% (79%) at 400 nm (200 nm) wavelength. All the mirrors are mounted with individual adjustment on a plane of 3.0 cm Rohacell foam reinforced by two films of 0.3 mm fibre glass epoxy.

The Cerenkov light is collected onto the 5 inch diameter photomultiplier tube cathodes with Hinterberger-Winston light funnels. These funnels have an entrance diameter of 21.7 cm and can accept light at angles up to 26° . They are aluminium coated to give a reflectivity of 85% (75%) at 400 nm (200 nm) wavelength.

The photomultipliers are shielded from the combined fringe field of the two (VSM and FSM) magnets. The shielding consists of 3 tubes of μ -metal in addition to a soft iron tube. It was not necessary to provide active shielding. The surfaces of the photocathodes are coated with a layer of 100 $\mu\text{gm/cm}^2$ of p-Terphenyl which acts as a wavelength shifter and gives a consequent increase in photo-electron yield.

The anode signals from the phototubes are split before being fed by one branch to ADC's [10] and by the other branch to discriminators [10] and subsequently to TDC's [10].

LED's are mounted both on each light funnel and at the entrance window (1 LED corresponding to 4 mirrors). This allows the on-line monitoring system to control the photomultiplier gain and mirror stability independently and also permits the overall response in terms of photo-electron yield to be checked.

3.4.3 Aerogel Cerenkov Counter CA

There is a gap in momentum between the identification capabilities of gas Cerenkov counters on the one hand and a time of flight system on the other hand. This gap has been filled by the use of a silica aerogel Cerenkov counter.

Two aerogel modules are symmetrically placed with respect to the beam (fig. 1) covering $\pm 9.8^\circ$ vertically for horizontal angles between 10° and 32° . Monte Carlo estimates of the particle density indicated that ≤ 1 particle per cell can be obtained in 90% of the cases if each of the two modules is subdivided into 10 cells. The surface area $150 \times 130 \text{ cm}^2$ of each module is therefore divided horizontally in two and vertically in five. The phototubes are supported in a frame, at the top of the upper cells and at the bottom of the lower cells, which is tilted at 9° to the horizontal (see fig. 3) so as to minimise the material between the target and the detectors WV1 and WV2. Each cell is tilted by 4.3° horizontally with respect to its neighbours to reduce the probability that an individual particle traverses more than one cell. The front faces of the cells have an area of $65 \times 30 \text{ cm}^2$ and the aerogel radiator is 18.5 cm thick, behind which the cell is completed by a 48 cm deep diffusing box all the interior faces of which are coated with millipore paper. The entrance and exit windows are made of 3 mm Rohacell, each side being covered with aluminised mylar. Five photomultipliers of 5 inch, surrounded by passive shielding of mu-metal and soft iron, are mounted on each cell and the light collection from the diffusing box is completed by diffusing cones.

The active aerogel volume is constructed of blocks $18 \times 18 \times 2.7 \text{ cm}^3$ with refractive index $n = 1.030 \pm 0.0007$. The tests which led to the final choice of aerogel depth and the light collection system are described elsewhere [11]; the main parameters of the counter, together with other identification detectors, are collected in Table II.

Despite the design efforts the anticipated mean number of photo-electrons is expected to be only one per photomultiplier tube per particle when the position of impact is near the mid plane of the detector. Special care had therefore to be taken to counteract stray magnetic fields which come from the VSM fringe field and from the compensating coils mounted on the C0 counter. Compensating coils were therefore mounted on each cell which reduce the losses with respect to zero field value to less than 5%.

The photomultiplier bases have a special design so as to give the maximum gain with 1% linearity precision for the range 0-9 photo-electrons and an operating high voltage of 2.7 kV. The photomultiplier anode signals are fed directly to ADC's [10].

LED's are mounted at the entrance cone of each photomultiplier and are continuously monitored to provide a precise calibration as a function of time in the region (~ 1 photo-electron) of interest. The absolute calibration is also monitored for variations due to high voltage instability and temperature variations and is maintained constant to better than $\pm 5\%$.

3.4.4 Status of Cerenkov Counters

Due to a combination of small effects, e.g. non-exact compensation of strong magnetic fields, edge effects of cells, multiple tracks in a cell, inclined tracks etc, the number of photo-electrons detected per particle is to date lower than was achieved in the prototype testing stage. For example for $\beta = 1$ particle C0, CA and C1 respectively detected 17, 4.2 and 5.0 photo-electrons on average.

3.4.5 Time of Flight Hodoscopes F1,2,3,4

Four large hodoscopes, located symmetrically with respect to the beam on either side of C1, provide time of flight measurements and hence identification of low momentum particles. There are two pairs of hodoscopes F1, F2 which cover horizontal angles from 9.75° to 34.0° , and F3, F4 which cover from 32° to 60° . The vertical acceptance is approximately $\pm 10^\circ$ for both pairs corresponding to the vertical aperture of the vertex magnet. The position in the overall system is shown in fig. 1 and in more detail in fig. 3.

The hodoscopes are designed so that F1, F2 match to the aerogel counter CA, and F3-F4 identify the very low momentum (< 1.5 GeV) tracks emitted at large angles or strongly bent by the VSM field. F1 and F2, each covering 206.3×160.0 cm², consist of 21 vertical plastic scintillator (Ne 110) strips 160 cm $\times$ 10 cm wide. The eight strips nearest to the beam are 4.0 cm thick and have no overlap, the other thirteen are 1.5 cm thick with an overlap of 0.2 cm. This arrangement provides the highest photostatistics in the region where higher momenta are expected. Each of F3 and F4 cover an area of 251.8×160 cm² and is constructed of 17 vertical strips 160 cm $\times$ 15 cm wide and 2.0 cm thick.

Each scintillator strip is viewed at each end by a photomultiplier (see Table II) via a simple fishtail light guide. The photomultipliers are passively shielded against the VSM fringe field by two layers of μ -metal and a soft iron housing, and their bases are optimised to obtain maximum time resolution (750 volts between cathode and 1st dynode at an operating voltage of 2.4 kV).

The cable from each counter to counting room is as short as possible, after which the anode signal from each strip is split. One signal is fed directly to ADC's [10] to provide off-line pulse height information, the other signal is discriminated [10] and the time recorded in TDC's [10]. In addition the discriminated signals from each end of the same strip give a logic signal which can be used in the construction of trigger logic.

In the analysis the pulse height (PH) information is used to provide a correction factor to the measured time of flight parameterised with an equation of the form $a + b/\sqrt{\text{PH}}$. Using such a correction procedure a time resolution ~ 200 psec is obtained near the photomultiplier, 230-250 psec from the centre of the strip and ~ 370 psec from the far end. The combination of the information from the two tubes in each strip then yields a time resolution $\sigma \sim 200$ psec, depending on impact position, for the stop time. The start time is given by the beam momentum station with $\sigma \sim 125$ psec. Taking into account these two factors for a mean flight path of ~ 520 cm, a probability > 0.95 is obtained with the separation of π and K up to 1.5 GeV and of K and p up to 2.5 GeV.

In order to achieve such a performance over a long running period the detector is carefully monitored. The on-line task checks the high voltage stability and with the help of LED's mounted on each strip the light collection efficiency and gain of the system are monitored.

The particle identification capability of the above detectors is illustrated in fig. 4.

4. Off-line Event Reconstruction

The reconstruction of events proceeds in the following stages:

- pattern recognition of muons and hadrons in the forward spectrometer using drift and proportional chambers information together with trigger hodoscope data;
- geometrical fitting of these tracks to obtain precise momenta and angles, determination of vertex parameters for beam and scattered muon and verification of the hardware trigger by the scattered muon;
- pattern recognition in the vertex spectrometer detectors and refit of streamer chamber and forward spectrometer track parameters, full vertex topology search and fitting;
- identification of particles and condensation of data.

Fig. 5 shows a flow chart of the complete analysis chain, the modules GEOM1, GEOM2 and SNOBAL are written within the ZBOOK [12] memory management package.

An important step in the reconstruction procedure is the geometrical alignment of the various detector planes. Reconstruction of straight-line tracks, obtained in special data taken with both magnets switched off, allows the evaluation of the small corrections to the survey position of detectors along the beam axis. A special run with a pion beam on a small and thin target in front of the streamer chamber enables corrections for the positions of the side detectors and the streamer chamber to be determined.

4.1 Pattern Recognition and Track Reconstruction in the Forward Spectrometer

This part of the analysis chain follows exactly the same procedure as outlined in [1]. However roadwidths and target pointing etc. are modified to take into account the vertex spectrometer magnet field.

4.2 Geometrical Event Reconstruction in the Forward Spectrometer

The geometry program (GEOM1) performs track fits and primary vertex fits for beam and scattered muon. The track fit procedure is identical to that described in [1].

Vertices are fitted using the single-track fits for beam and like-sign muons as input. A chi-squared fit is made to find the point of closest approach without improving the track parameters. These vertices may be anywhere inside or outside the VSM field. The reconstructed scattered muon is tested to see if it fulfils the hardware trigger conditions.

The output of the program is a Data Summary Tape (Maxi-DST) which contains fitted track and vertex parameters, the line vectors from the reconstruction program, and the raw event data. Condensed information on track and vertex parameters, trigger conditions and detector hit patterns used in track reconstruction are also written to a Mini-DST. This tape is used for

studies of forward spectrometer reconstruction efficiencies and as input for streamer chamber film measuring systems to select the events wanted for measurements. Streamer chamber film analysis is reduced by a factor 4 by demanding a triggered muon with vertex in the target plus loose kinematic cuts.

4.3 Reconstruction in the Streamer Chamber

The film is measured in the different laboratories using semi-automatic film measuring devices. On most pictures non-interacting beam tracks which pass through the chamber during the sensitive time (~ 10 tracks/picture) confuse the forward region. Tracks are measured if they emerge from this confused region giving a measurable length of more than 20 cm in space. Low energy tracks are measured irrespective of momentum except for minimum ionising tracks for which a minimum momentum of 100 MeV is required. This latter cut is applied to reject low energy electrons.

Measurements of 3 views of the streamer chamber picture are reconstructed in space using a modified version of the HYDRA Bubble Chamber Geometry Program [13]. The main differences relate to the fact that no vertices are required for matching of track images and reconstruction in space. Fitted parameters for tracks, calculated main vertex and measured secondary vertices are written to tape and merged with the information on Maxi-DST.

4.4 Pattern Recognition and Geometrical Reconstruction of the Complete Event in Vertex Spectrometer

This program (GEOM2) combines tracks from reconstruction in the forward spectrometer and the streamer chamber (if available) and searches for extra tracks in the vertex spectrometer which are not measurable in the streamer chamber and do not pass through the acceptance of the FSM. Vertices are fitted to establish the event topology and kinematics.

Tracks measured in the streamer chamber are extrapolated to the detectors in the vertex system (PV, POC, WV, W12). Errors on track parameters are propagated, taking into account multiple Coulomb scattering and energy loss,

and hits recorded inside the roads are used to fit lines in space.

Pattern recognition in PV123 first associates hits in the two vertical planes to define possible values of y and dy/dx ; these are then inserted into the relations between plane orientations in butterfly geometry [14] to determine slopes and impacts for the space lines. Pattern recognition in POC uses the weighted mean of adjacent clusters in every pair of staggered planes in the 4 plane orientations to associate projections. Slopes and impacts of the line in space are obtained by fits to the hits in the individual planes. Pattern recognition in WV finds lines in y and z projections and associates them via hits in the delay line planes. Pattern recognition in W12 finds lines in y and z projections and uses hits in theta planes for association.

Track parameters and errors are improved by refitting with lines in up to 3 detectors.

Tracks from forward spectrometer reconstruction are represented at a fixed plane in the field-free region between the two magnets. They are tracked towards the target to detectors PV2 and POC. Pattern recognition and refits of track parameters are done as described for streamer chamber tracks.

Muon vertices from beam and like-sign muons are refitted with the improved track parameters and are saved. Hadron tracks which pass within a minimum normalized distance of closest approach to the muon vertices are included in the fits for hadron vertices. Vertex positions from muon vertices and vertices measured in the streamer chamber are used as first approximations. Tracks connected at these vertices are considered as "safe" and are never disconnected. New vertices are then found from pairs of unassociated tracks or pairs of unassociated and associated "unsafe" tracks. Groups of pairs can be clustered to form vertices of higher multiplicity. Finally the complete topology of the event is determined after consistency checks.

Additional tracks in the vertex spectrometer which do not pass through the FSM aperture are found from spline fits through the main vertex plus unused lines in the vertex detectors.

The output from this program is again a Maxi-DST which contains the total geometrical and kinematic information together with the raw event data. Information on this tape can be reprocessed through earlier steps in the analysis chain.

4.5 Particle Identification and Data Reduction

Identification of particles requires precise information on track momenta and position in the various detectors as discussed above. Charged particle identification is carried out with the Cerenkovs C0, C1, C2 [15], CA and the Time Of Flight hodoscopes Fl-4. In each detector the expected amplitudes for various mass hypotheses are calculated taking into account background and multiple tracks. In general the tracks traverse more than one detector with particle identification and thus results can be matched and global probabilities for mass assignments obtained. In addition there are independent measurements of electromagnetic showers in the H2 Calorimeter and in the Lead Glass detector.

Within the procedure of data reduction there are processors to study the beam phase space, to normalise the intensity for cross section measurements and also to make statistical analysis of the reconstruction process.

Selected events can be written in a condensed form onto Mini-DST's. This includes the entire set of kinematics parameters as well as sufficient extra information to allow high statistics studies of the performance of the detectors, recalculation of global particle identification, normalization, etc.

Data files written by a Monte Carlo program can be compared with real data or processed through the whole analysis chain in order to study performance of programs at every step of the procedure outlined above.

4.6 Experimental Resolutions

The geometrical resolution for tracks measured purely in the forward spectrometer system is similar to that obtained when only this part of the apparatus was in operation, i.e. $\frac{\sigma(p)}{p} \sim (20 + 1.1 * p) * 10^{-4}$ (GeV/c). The addition of position information from proportional chambers PV2 or POC improves this by approximately a factor of two but has little effect on the resolution in angle.

For tracks measured in the streamer chamber alone the resolution in momentum is approximately $\frac{\sigma(p)}{p} \sim (10 + 9 * p) * 10^{-3}$ (GeV/c) and the addition of information from PV2 or POC does not significantly improve this since the extension of the lever arm is minimal. If a line from WV or W12 is available, however, the improvement is in the order of a factor 5 giving approximately 5% resolution at 20 GeV/c. The vertical and horizontal angle resolutions are also improved from 6 and 8 mrad to 0.4 and 2 mrad, respectively, for tracks with momenta greater than 10 GeV/c. Below 10 GeV/c the angular resolution is worse due to multiple Coulomb scattering.

As mentioned above, the interaction vertex is initially defined using only the incident and scattered muon trajectories. This gives mean resolutions of $\sigma_x \sim (1.25 + 2/p)/\theta$ mm (θ in radians, p in GeV/c) along the beam direction and $\sigma_y \sim \sigma_z \sim 0.6$ mm transverse to it. The large number of hadrons produced in the interaction and their precise measurement close to the vertex in the streamer chamber leads to a reduction in these uncertainties to typical values of $\sigma_x \sim 7$ mm, $\sigma_y \sim 0.3$ mm, $\sigma_z \sim 0.5$ mm.

Having determined the vertex position with some precision, it is then possible to measure the momenta of particles which do not enter the forward spectrometer and cannot be measured in the streamer chamber because they are in the beam region. This comparatively small class of tracks can be measured with a resolution of $\frac{\sigma(p)}{p} \sim (10 + 0.3 * p) * 10^{-3}$ (GeV/c) provided that measurements in both of PV or POC and WV or W12 are available.

Conclusions

The operation of the complete spectrometer (vertex and forward) began in the middle of 1981 using the liquid hydrogen target and has successfully taken data with a total flux of $\sim 10^{12}$ incident muons. Preliminary particle spectra were presented at the Paris Conference in July 1982, and physics results are anticipated within the next year. The future programme also involves an equivalent amount of data with the deuterium target plus some with solid target during 1983.

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- the SPS survey group for the difficult task of surveying with precision so many detectors;
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TABLE I

Monte Carlo estimates of charged hadron distributions
for muon energy of 280 GeV

Charged multiplicity	8.3
Mean hadron muon momentum (GeV/c)	9.
Proportion of all hadrons in PV2	0.83
Proportion of all hadrons in PV1-3	0.05
Proportion of all hadrons in WV1-2	0.2
Proportion of all hadrons in outer TOF	0.09
Mean momentum through CA - outer C0 (GeV/c)	2.6
Mean momentum through C1 - central C0 (GeV/c)	14.

TABLE II

Detector	Horizontal Angle coverage (degree)	Sensitive** Area cm ² (entrance window)	Cell* size cm ²	Sensitive radiator (n=refractive) index	Total PM's number (and types)	Material* thickness (in unit x ₀)	Threshold values $\pi / K / p$ (GeV/c)
Time of flight	F1-2 $\pm(10 - 34)$ F3-4 $\pm(32 - 60)$	160 x 206.3 160 x 251.8	160 x 10 160 x 15	NE 110	84 (XP2230B) 68 (XP2020)	(0.095)**** 0.036 0.047	(separation π/K 1.5) (separation K/p 2.5)
Cerenkov CA	$\pm(10 - 32)$	150 x 130	65 x 30	n-1=.030 (aerogel)	100 (RCA8854)	0.141 ***	.6 / 2. / 3.8
Cerenkov C0	-32 - +32	300 x 100	12 x 14 25 x 28	n-1=.00171 (neo-pentane)	128 (EMI9829QA) 16 (RCA8854)	0.016	2.4 / 8.4 / 15.9
Cerenkov C1	-9 - +9	108.6 x 143.3	13.6 x 18	n-1=.000282 (nitrogen)	58 (RCA4522)	0.026	5.6 / 20.0 / 38.0
Cerenkov C2 [15]	-7 - +7	150 x 300	22.5 x 25	n-1=.67 $\cdot 10^{-4}$ (neon)	78 (XP2041)	0.03	20 / 70 /

* perpendicular to the front surface
 ** each module if any
 *** mainly due to the aerogel itself
 **** strip of 1.5 cm thickness (resp. 4 cm)

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FIGURE CAPTIONS

- Fig. 1 Plan view and side view of the spectrometer (vertex and forward).
BH are beam hodoscopes, V's veto hodoscopes, H's scintillator hodoscopes, P's-PO's-PV's proportional chambers, W's drift chambers, C's Cerenkov counters, LG lead glass detector, SC streamer chamber.
- Fig. 2 Sketch of the vertex magnet together with the streamer chamber.
1: data box; 2: optical grid; 3: foil and grid window; 4: fiducial mark; 5: grid electrodes; 6: inner adapter; 7: spark gaps; 8: capacitors of the Marx generator; 9: diffusion pump.
- Fig. 3 Side view of the vertex spectrometer in the 22° from the VSM centre (as shown in fig. 1). The cross-hatched area of CA shows the aerogel.
- Fig. 4 Summary of particle identification with various Cerenkov's and Time of Flight detectors. II shows threshold values of detectors; I is for outer region in the horizontal plane ($\pm 9^\circ$ to 32°) and TOF up to 60° up to 16 GeV momentum; III is for central region in the horizontal plane (-9° to $+9^\circ$) from 2 to 100 GeV momentum; I and III show the identification capability: full line implies complete identification for corresponding particle; dotted line implies ambiguity between corresponding pair of particles. The logical combination signal (C) or no signal ($\bar{C}$) are explained in each case.
- Fig. 5 Flow chart of the analysis chain. FILTER performs OFF LINE filtering of the triggers into various output streams. RECONS is the pattern recognition program in the forward spectrometer detectors. GEOM1 does the track fits in the forward spectrometer detectors to get the primary vertex. GEOM2 performs pattern recognition in the vertex spectrometer detectors and refits the tracks using the streamer chamber geometry output (SC.GEOM). SNOBAL adds the particle identification information to output the DST. (MC and SC stand respectively for Monte Carlo simulation procedure and streamer chamber apparatus).

0 1 2 3 4 5m

FIG. 1

FIG. 2

FIG. 3

FIG.4

FIG. 5