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**UPGRADED MUON DETECTION SYSTEM FOR UA1
BASED ON LIMITED-STREAMER TUBES**

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ABSTRACT

We describe the construction and performance of the improved muon-detection system of the UA1 experiment. The new position detectors, which complement the original muon-detection system based on large planar drift chambers, are limited-streamer chambers with a total surface of 800 m². The coordinate parallel to the wires is read out through the specially developed STAR electronics that integrates and digitizes the signal from the strips. The intrinsic spatial resolution, determined in a test beam, is 400 μ m, that achieved so far in the real system is 1.2 mm. The efficiency is evaluated to be $94.9 \pm 0.6\%$.

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1. INTRODUCTION

This paper describes the first large system of limited-streamer tubes operated at a high-energy accelerator and designed as a precision position detector, installed to improve muon identification and measurement in the UA1 detector. These limited-streamer chambers complement the original muon-detection system [1], based on large planar drift chambers. Details of other UA1 detector components are given elsewhere [2].

An energetic muon produced in a $p\bar{p}$ interaction traverses the following detector elements (shown in fig. 1). The central detector, a large drift chamber that operates in a horizontal dipole field of 0.7 T, measures the muon's momentum. After leaving the central detector, the muon passes through the electromagnetic and hadronic calorimeters (≈ 8 interaction lengths at normal incidence). It then penetrates additional iron shielding (60 cm on the sides, 120 cm in the forward regions, 40 cm on the bottom) instrumented with the new limited-streamer chambers. Finally, it encounters the muon drift chambers, consisting, on five sides, of two layers, separated by 60 cm, each containing two planes for both coordinates. Space limitation constrains the bottom drift chambers to one layer with four planes measuring only the coordinate perpendicular to the beams.

Here we discuss the motivation for installing the limited-streamer chambers, their construction and electronics, practical details of their operation, and an evaluation of their performance.

2. MOTIVATION AND TECHNIQUE

The limited-streamer chambers were designed to contribute to muon physics in several ways: they provide a momentum measurement independent of the central detector to help identify secondary muons from π and K decays (the dominant background in muon physics); they give additional information for triggering; they aid in the matching of the central detector tracks to the muon drift-chamber tracks and in some cases measure a coordinate not measured by the muon drift chambers.

The momentum measurement is obtained by mounting limited-streamer chambers in walls of magnetized iron as shown in fig. 2. The two walls, one on each side of the detector, are built by stacking eight equal carbon-steel blocks ($480 \times 165 \times 68 \text{ cm}^3$) in a configuration four blocks high and two blocks wide (along the beam direction). The blocks themselves consist of three plates 20 cm thick, bolted together to form two gaps of 4 cm within the wall. Chambers are mounted within these gaps and on the surface of the wall nearest the beam. Four coils in each wall (one for each vertical pair of blocks) magnetize the iron to 1.25 T. Figure 3 shows the flux pattern in two adjacent pairs.

The magnetic field deflects a muon at normal incidence by an angle:

$$\Theta(B = 1.25\text{T}) \simeq 225/p \text{ (GeV) mrad}$$

to be compared with the r.m.s. deflection due to multiple Coulomb scattering of

$$\Theta_m = 90/p \text{ GeV (mrad)} .$$

To evaluate the resolution that can be obtained in the momentum measurement by the improved muon system, consider the geometry shown in fig. 2. The momentum can be obtained by measuring S , the difference between the actual position of the muon in the first limited-streamer-tubes plane and the projected position after bending by the field.

The muon drift chambers provide the direction of the track after the muon passes through the iron. The momentum resolution is then

$$\Delta p/p = \sqrt{\sigma_{ST}^2 + \sigma_{ms}^2 + \sigma_d^2}/S ,$$

where σ_{ST} is the resolution of the limited-streamer tubes, $\sigma_d \approx 0.5\text{--}0.8$ mm is the expected projected error from the muon chambers, and $\sigma_{ms} \approx 30/p$ (p in GeV/c and σ_{ms} in mm) is the contribution from multiple scattering in the iron.

Measurements performed both with radioactive sources and in a test beam [3] have shown that the limited-streamer chamber resolution σ_{ST} is in the same range as σ_d (0.5–0.8 mm). Under these conditions multiple scattering gives the biggest contribution $\Delta p/p \approx 44\%$ up to 60 GeV (37.5 GeV) for $\sigma_d = \sigma_{ST} = 0.5$ mm ($\sigma_d = \sigma_{ST} = 0.8$ mm).

In this preliminary evaluation the information available from the two middle limited-streamer planes is not used; it is then expected that an appropriate track-fitting algorithm will provide better resolution figures.

The limited-streamer chambers can also be used to improve the on-line track reconstruction for the trigger. The hardware muon trigger is currently made exclusively with the muon drift chambers by looking at patterns of hit wires that point back to the interaction region within ± 150 mrad. In addition, since the 1984 data-taking period, an on-line software algorithm that uses the drift-time information from the muon drift chambers and the central detector is used to reject false triggers. With more than eight interaction lengths to absorb hadrons, the dominant muon source is medium energy π and K decay in the central detector volume and the angular cuts of the trigger are effectively p_T cuts on the steeply falling momentum spectrum. In the off-line analysis these events can mimic a high-momentum prompt muon if the transverse momentum kick from the decay balances the deflection of the particle in the magnetic field. The measurement of the momentum of the track, independent of that of the central detector, provided by the improved muon system, will help in considerably reducing this background.

The background trigger rate in the forward regions increases steeply at increasing rapidities, preventing the inclusion of the parts of the muon drift chambers nearest to the beams in the hardware trigger. The limited-streamer chambers will be used to improve the background rejection in this environment.

A layer of limited-streamer chambers has been installed in the bottom of the experiment because, as mentioned in the introduction, the muon drift chambers in this region only measure the coordinate orthogonal to the beam line.

Finally, in the study of heavy flavours produced in $p\bar{p}$ interactions the muons from their semileptonic decays are embedded in hadronic jets, and are hence more difficult to separate from background than the isolated leptons coming from W and Z decays. Having more measured points along the candidate muon track should aid in reducing matching ambiguities and produce a cleaner sample of validated muons.

3. THE MECHANICS OF THE SYSTEM

3.1 Description of the tubes

The detection planes were constructed from plastic limited-streamer tubes with strip readout. The tubes are similar construction to those of ref. [4]. Each tube consists of a PVC envelope of width 16.7 cm and height 1.3 cm, divided into two halves along its length by an internal separator. Each half contains 8 high-voltage anode wires of 1 cm separation in an extruded PVC open profile coated with graphite to give a low resistivity (less than 2 k Ω per square as measured at production time) and closed with a PVC cover of high resistivity (greater than 3 M Ω per square) to ensure good transparency. In the first production series we coated the PVC covers with graphite at such high values of resistivity but it turned out to be difficult to reach quiet operating conditions (stable low current) with the tubes built in this way. The most outstanding characteristic was the appearance of a glow discharge on some regions of the wires facing the high resistivity plane. The same behaviour has

been observed in ref. [5]. Most of the production was therefore made with non-coated PVC covers running the streamer tubes in the 'electrodeless' mode [6].

The wires, which are supported every 50 cm, are silver-plated Cu/Be alloy of 100 μm diameter, held at a tension of 250 g by being soldered onto small printed circuit boards which slot into each end of the PVC profile. At one end each wire is terminated on 220 Ω , the characteristic impedance of the wire plus tube line, and then joined, eight at a time, to a common high-voltage input, two per tube. The envelopes are closed with PVC stoppers, heat-welded on, with input for gas and high voltage at one end. A tube opened up is shown in fig. 4. The passage of the gas flow is in one side of the PVC stopper, down one side of the envelope and back and out on the other side.

3.2 Description of the chambers

A standard chamber has external dimensions of 4.67 m $\times$ 1.64 m and provides the measurement of two (X and Y) coordinates. Only the coordinate parallel to the wire is read out for each tube by integrating and digitizing the pulse induced on the strips, which are perpendicular to the wires and located outside the tubes on the side of the transparent cover.

A chamber is made of 9 long and 27 short tubes sandwiching the pick-up strips. These strips are the elements of the detector that define the precision of the measurement; construction and assembly procedures were selected to achieve an absolute precision on the location of each strip of 100 μm .

The strips are obtained by removing Al from one side of a PVC supporting ribbon, 20.3 cm wide, 1 mm thick, clad on both sides with Al foils (100 μm thick). To achieve the required resolution, this ribbon was positioned and kept flat on an especially designed machine bed by vacuum. Reference holes, 60.96 cm apart, were drilled in the middle of the ribbon. Finally the strips were cut with a precision (100 μm over 5 m length) multiheaded milling machine, which, running on two rails, produced 16 strips 10.2 mm wide and 2.5 mm spaced.

The structure of a chamber module is shown in fig. 5. The tubes were glued without any special accuracy (1–2 mm) on the external support plates (2.5 mm Al). The precision element, in the middle of the module, was made by glueing the strips on both sides of a 3 mm thick PVC plate. To ensure the accurate positioning of the strip ribbon, reference holes were drilled in advance on the PVC plate on a reference table; the accurate positioning of the strips was then done by pinning reference holes on the ribbon to the holes in the plate.

The position of the coordinate grid thus created is referenced to the outer aluminium plate and thus to its hanging supports only through the right angle made by the plate edges. A final measurement of the alignment with respect to the rest of the UA1 apparatus must be done using cosmic rays. The most serious alignment problem comes from the non-rigid structure of the chambers due to the need to fit them into the 4 cm spaces in the iron walls; in practice the chambers sag up to 0.5 mm. This effect is expected to degrade the system resolution from the 400 μm measured over small areas in test studies [3].

The induced pulses are integrated and digitized with 8 bit resolution by the especially developed STAR readout modules [7]. Each module reads 32 strips and is directly connected to one end of these strips. The STAR modules are 40.64 cm (32 strips) long, 9.5 cm wide, and are located inside the chamber module. There are 11 STAR modules to read out the short strips, 4 to read out the long ones. The dead space of the detector unit due to the STAR modules amounts to 7.3% of the total.

3.3 Layout of the chambers

The chambers are mounted on five sides of the UA1 detector: on the two sides, in the two forward directions, and below the detector.

On the sides of the experiment the three layers of chambers are hung on the inner face of the magnetized iron wall and in the two gaps. The long tubes are horizontal and the short tubes vertical.

Each layer contains 8 chambers so requiring a total of 48 chambers. In the forward directions the chambers are hung with the long tubes vertical, on the inner face of the shielding walls as shown in fig. 6. There are two layers, of 12 chambers each, the innermost being displaced 15 mm downwards and 265 mm outwards from the beams in order to maximize the geometrical efficiency. There are a total of 48 chambers on the two forward walls.

Below a floor of iron shielding 40 cm thick twelve chambers are deployed on top of the existing muon drift chambers. The four central chambers are of standard-size, the other eight, owing to space limitations, have standard length but reduced width. Finally, the total number of limited streamer chambers in the system is 108.

4. OPERATION OF THE CHAMBERS

There are four aspects relevant to the operation of the chambers:

- i) The Streamer Tubes Analog Read-out (STAR) of the strips
- ii) High-voltage control and monitoring
- iii) Low voltage
- iv) Monitoring of the gas mixture.

Each of these will be described below.

4.1 Analog readout

The readout of the strips is performed using the STAR system and will be fully described elsewhere [7]. In each module 464 strips (112 long, 352 short) are read out by 15 STAR cards (each serving 32 channels). The STAR cards integrate and shape the pulses from the strips, sampling and holding in analog form the peak value. Analogy-to-digital conversion of the stored charges is performed on external request with separate gain correction for each channel and the resulting digital data are stored in a double buffer to allow event derandomizing. Data selection and filtering are achieved through an analog threshold, a Mask and a Data-Ready Flag. On each card a calibration system can inject equal charges in all the channels to determine the gain corrections needed to equalize them. All STARs of one chamber are connected to a 34-way flat cable, called a STAR bus. Up to 120 STARs can be read out on a STAR bus by a STAR controller (SC), but in practice only 6 chambers (90 STARs) are read out on each STAR bus. Hence there are 18 SCs in the system, 8 for the side chambers, 8 for the forward chambers, and 2 for the bottom chambers. The STAR controllers reside in a VME crate and are read out by CPUA1 modules [8] based on the MC68010 Central Processor Unit (CPU), through a VMX bus. Nine CPUA1 modules are used, seven for parallel data acquisition, one for data sampling, and one as the supervisor.

The Supervisor CPU is connected via a VMX bus to a Dual Port Memory in the main data-acquisition system of the experiment and handles the transfer of data from the acquisition CPUA1s. The Monitor CPU obtains sample events through a VMX bus from a Dual Port Memory module (FIFO) used as an event buffer which is filled via the VME bus by the Supervisor CPU. This monitor CPU records several histograms to track the performance of the readout and produces an event display through a colour graphics card which resides in the same VME crate as the CPUA1s. A terminal is connected to the Monitor CPU and allows, as well as data acquisition, control hardware tests, calibration, pedestal measurements, etc.

The total system of 108 chambers contains 1604 STAR modules or about 50000 channels. After zero suppression a typical event contains only 700 bytes. This data reduction comes about because only those STAR modules which detect a strip above a preset Analog Threshold set the Data-Ready Flag, digitize the data, and are read out. Gain correction is performed on the STAR modules, pedestal subtraction in the STAR controllers, and the remaining zero data skipping in the CPUA1s.

4.2 High voltage

Eight anode wires share a high-voltage input giving 2 cables per tube. For the short tubes these are supplied with 1 cable because of the limited space available along the edge of the chamber. The cable used is RG316/U, which has a characteristic impedance of $50\ \Omega$ and an external diameter of 2.6 mm. There are 18 (27) high-voltage cables connected to the long (short) tubes per chamber which are brought to a distribution box close to the chamber. In this box each channel is in series with a $27\ \text{M}\Omega$ resistor connected to a common high-voltage input. A monitor point is also provided through a $4.7\ \text{nF}$ capacitor for each channel. Each chamber can therefore be supplied by a single high-voltage cable (RG58C/U) from the control room. For the side chambers 4 cables are used to supply a set of three chambers in order to provide different operating voltages for the chambers which have graphite coated covers as opposed to no coating. Approximately 25% of the planes in the sides have graphite coated covers and these are operated at $+4.4\ \text{kV}$ whereas all the other chambers in the system operate at $+4.7\ \text{kV}$. The tubes were extensively tested to 300 V above their operating voltages before installation.

In the control room for each of the RG58C/U cables there is a relay which shunts the chamber to ground when opened. Roband 5 kV power supplies [9], modified to give a positive voltage supply, provide voltage to 4 relays. In practice, 18 supplies are used for the side chambers, 12 for the forward chambers, and 3 for the bottom chambers. Sixteen relays are mounted in a single box resulting in 9 boxes for the system.

4.3 Low voltage

The STAR modules on the chambers require $+5\ \text{V}$ and $\pm 12\ \text{V}$ low voltage power supplies. Gould switching power supplies [10] are used and located close to the chambers. Each supply can deliver 60 A at $+5\ \text{V}$, 20 A at $-12\ \text{V}$ and 10 A at $+12\ \text{V}$ and is used to power three chambers. Hence there are 36 supplies in the whole system. The supplies can be switched on and off remotely using opto-couplers and from each supply the three voltages are carried upstairs to the control room for monitoring.

4.4 Gas

During the production, each tube was tested for gas tightness by pressurizing and measuring the leak rate. A final test was performed on assembled chambers and a chamber was considered tight if the leak rate was less than 0.5 litres per hour at 30 mbar over pressure. In the experiment the chambers are operated at approximately 5 mbar over pressure. The gas mixture used in the chambers is 75% isobutane and 25% argon. Each chamber has a flow meter on the input and a return bubbler on the output and hence can be isolated if necessary. The isobutane is monitored on the input to the chambers with a Binos gas analyser [11], which gives a current output for monitoring corresponding to 20 mA full scale at 100%. The oxygen concentration on the output from the chambers is monitored using a Teledyne analyser which gives a voltage output for monitoring corresponding to 1 V full scale.

5. CONTROL AND MONITORING

The readout system is controlled through a CPUA1 in the VME data-acquisition crate, as described above. Control and monitoring of the high and low voltage and gas is made through a CAVIAR processor [12] using a RS232C serial bus to communicate with the RS232C Multiport Control System (MCS) [13]. In this system there is a master or RS232C interface unit which can address up to 7 drivers. Each driver can address up to 127 slave units. In practice, owing to current limitations, only 25 slave units on a single bus are possible. A slave unit can address the following units:

- i) two 16-channel outregisters, or
- ii) four 32-channel DAS extension units.

Each outregister unit has 16 opto-coupler transistors on the output at the front panel which can be switched to any desired pattern. These units are used in two control functions. Firstly, the low-voltage supplies and, secondly, the high-voltage relays are switched on and off using these units.

Each DAS extension unit is able to digitize up to 32 input voltages in the range 0 to +5 V to 8-bit precision, i.e. a least count of 20 mV. These units are used to monitor the output voltages from the low-voltage power supplies. Resistive dividers are used to bring voltages into the measurement range. The outputs from the gas analysers are also digitized using these units, allowing a continuous monitoring of the gas mixture.

A second type of slave unit completes the system, namely the HV SLAVE. This card resides in the Roband high-voltage power supply and contains a 12-bit DAC and a 12-bit ADC for writing and reading the high voltage, respectively. The 12-bit precision corresponds to a least count of 1.22 V for control and monitoring. It is also possible to monitor the current to 12 bits so that the full scale of 500 μ A can be read down to 0.122 μ A.

The whole RS232C Multiport Control System is contained in three 3U EUROPA crates with G64 backplanes. The logic parts are mounted on standard boards of 160 mm height. The system is based on the following integrated circuits: namely MC14469 for the serial interface, SN75116 for bus transceivers, and low-power Schottky logic. The maximum baud rate allowed is 4800; however this is certainly not a limitation given the control and monitoring tasks required. The program in the CAVIAR continuously checks that all the voltages are at the required values and records the current from the high-voltage supplies and the gas mixture. A colour monitor is continuously updated with this information and alarms are given when necessary.

6. PERFORMANCE

After a running-in period with a limited number of chambers installed during the run at the end of 1984, the full system of 108 chambers was installed for the 1985 run. During this four-month run the whole system operated smoothly; only one chamber was not readout owing to a problem on some STAR cards that killed the STAR bus and one layer of tubes of another chamber was not operable owing to a gas leak. High-voltage problems resulted in the isolation of 23 tubes or less than 0.6% of the tubes in the total system. This failure of 2% of the hardware components occurred at the beginning of the run and in general was caused by mechanical damage at the time of installation.

In order to estimate the global efficiency of the system to detect muons we have used a sample of cosmic-ray triggers. This data sample was collected without any requirement from the streamer-tube system. Muons with momenta as measured by the central detector, greater than 8 GeV/c were selected; their track can easily be extrapolated to the detector planes. By asking how many clusters have been observed compared to those expected from the extrapolation we obtain an efficiency of $94.9 \pm 0.6\%$, consistent with what we expected from geometrical dead spaces.

The most stringent demand of spatial resolution is on the side walls, where a momentum measurement must be performed by the system. With our geometry of the tubes and the strips the charge induced by a streamer spreads on two or three contiguous strips. Our algorithm to evaluate the coordinate effectively fits the integral of a Gaussian function over each strip to the observed charges. As reported in ref. [3] the resolution achieved in a test beam was 400 μ m r.m.s. over 40 cm² at normal incidence.

Different sources of errors can contribute in the final 800 m² system: in particular, i) a systematic error proportional to the distance to the wire is present for tracks whose direction is not in the plane of the wire and the normal to the chamber; ii) the planarity of the chambers is only partially

achieved owing to their non-rigid mechanical structure; iii) the relative positions of different detector components are not perfectly known.

To evaluate the spatial resolution we have used a sample of cosmic-ray tracks crossing the UA1 detector sidewise, with zero field in the side walls. Tracks with momenta larger than 8 GeV/c, as measured by the central detector, were used to translate and rotate each limited-streamer-tube chamber with respect to the muon drift chambers behind it. Having aligned each chamber with respect to the original muon system, we have evaluated for both coordinates the difference between the position of the track measured in the threshold limited-streamer-tube layer and that expected from the measurements in the first and in the third. If σ_{ST} is the spatial resolution of our system that we want to determine, the r.m.s. of the distribution of the difference is:

$$\sigma_T = \sqrt{3/2 \sigma_{ST}^2 + \sigma_{ms}^2},$$

where σ_{ms} is the error due to the multiple scattering in 20 cm of iron. This is, of course, different from track to track but is typically between 0.5 and 0.7 mm in our sample. From the observed distribution of the difference we evaluate $\sigma_{ST} = 1.2$ mm. The distribution of the difference divided by σ_T , with this value of σ_{ST} , is shown in fig. 7; it is a normal distribution with a zero mean and unit variance.

The three points measured in the iron wall by the limited-streamer chambers and the direction given at their exit of the wall by the muon drift chambers provide an independent measurement, p'' , of muon momenta. We have evaluated the resolution of this measurement using a sample of cosmic rays crossing the UA1 detector. We show in fig. 8 the quantity $\sigma(1/p'')/(1/p'')$ as a function of $1/p''$. This quantity reaches 1 at about 25 GeV and has fluctuations of order unity at about 5 GeV, thus defining the useful range for measuring momenta. The best resolution is about 30% at 8 GeV.

In fig. 9 we compare $1/p''$ with the momentum measured in the central detector and extrapolated to the wall $1/p^{CD}$. The agreement between the two measurements is evident; the spread of the points is compatible with the resolution evaluated above.

7. CONCLUSION

The improved muon detection system of UA1 has been fully operational since August 1985. The detector of 800 m² total area, is based on the novel technique of limited-streamer tubes with analog readout. The specially developed STAR electronics is capable of an intrinsic resolution better than 400 μ m. The resolution achieved so far in the full scale detector is 1.2 mm, comparable with the other sources of error in the measurement of the coordinates (multiple scattering and extrapolation from the original muon chambers).

During the four-month run at the end of 1985 both the chambers and the 50,000 channels of readout electronics operated smoothly without any serious problem. The improved muon detection system will add to the trigger capability, the background rejection power, and to the quality of the muon data of the UA1 experiment, enlarging the range of muon physics of the experiment.

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Figure captions

- Fig. 1** Plan view of UA1 apparatus showing the side walls (A), the side chambers (B), the forward iron (C), the forward chambers (D). The chambers of the original muon system are shown as boxes outside the shaded iron. The bottom chambers (not shown) lie in between the rails (E).
- Fig. 2** Track through the side wall and muon chambers showing a deflection due to bending in the magnetic field.
- Fig. 3** The flux pattern in the iron of 4 blocks of the side wall.
- Fig. 4** Photograph of a tube opened up to show the profiles and printed-circuit boards. The covers in this tube are graphite coated and are seen taped to the profile. Also seen are the wires, though the terminating resistors are not as they are on the underside of the printed circuit board.
- Fig. 5** Expanded view of a chamber to show its construction. From front to back we have: an aluminium plate (2.5 mm); short tubes (13 mm); long pickup strips 1 mm, PVC plate (3 mm), short pick-up strips on the reverse side (1 mm), long tubes (13 mm), and aluminium plate (2.5 mm), giving a total thickness of 36 mm. The reference holes are shown as small crosses.
- Fig. 6** Photograph of one wall of the forward chambers with the central calorimeter rolled out. There are two layers of 12 chambers. Also seen at the bottom are iron shielding blocks which cover the bottom muon chambers and the additional limited-streamer-tube chambers.
- Fig. 7** Distribution of the difference between the coordinate measured in the middle plane of the side walls and the value expected from the interpolation of the measurements of the other two planes; the difference is divided by the total expected resolution. The curve is a Gaussian with zero mean and unity variance.
- Fig. 8** Relative error on $1/p$ versus $1/p$ for a sample of cosmic rays with $p > 8 \text{ GeV}/c$, with a 1.2 T field in the iron walls.
- Fig. 9** $1/p$ as measured by the upgraded muon system versus $1/p$ as measured by the central detector for the same sample as in fig. 8.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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Fig. 6

Fig. 7

Fig. 8

Fig. 9