4 Muon system

4.1 Iron instrumentation

4.1.1 The limited streamer tubes

The iron yoke of the main solenoid magnet surrounds all major detector components of H1. It is interleaved with slits which are equipped with limited streamer tubes (LST). They serve as hadronic tail catcher and for the measurement of penetrating tracks. Luranyl [109] was used to build the chambers since PVC tubes [110] were excluded for safety reasons [111]. Luranyl is a halogen free plastic material which can be extruded with sufficient precision. It can also be coated with the graphite paint needed to obtain the required surface resistivity. Some features are listed in Table 11.

Density	1.06 g cm^{-3}
Thermal expansion (23 – 80 °C)	0.6 – 0.7 $\times$ 10^{-4}
Surface resistivity	10^{14} Ω
Softening point	100 °C

Table 11: Basic properties of Luranyl [109].

The basic chamber elements are extruded eightfold profiles with a cell surface size of 10×10 mm^2. The mechanical precision achieved is 0.1 mm, the straightness of the profiles is better than 1 mm per m. The profiles are coated with graphite paint to yield a low surface resistivity of $\approx 10-30$ k$\Omega/\square$. The HV is applied to this surface. A silver coated Cu-Be wire of 100 μm diameter is at ground potential. The wire is kept in place by spacers every 50 cm. The profiles are closed with a Luranyl cover with high resistivity of ≈ 10 M$\Omega/\square$. The profiles are grouped by pairs in a gas tight box of Luranyl. All connections to the chamber are provided on one end of the box. Several boxes are put together to form a complete streamer tube layer. On the high resistivity side planes of either strips or pads are glued onto the boxes containing 16 active elements. The layers are put onto an aluminium plate and wrapped into a non conducting foil to guarantee electrical insulation.

A schematic view of the basic structure is given in Figure 40, while Figure 41 displays the configuration of the planes within the iron together with an indication where strips and pads are located. As an example, the instrumentation of a barrel octant is shown. Starting from the interaction point there is first a so-called muon-box installed in front of the iron containing three layers (two layers with strips perpendicular to the wire direction and a third layer with pads). Pad layers are also installed in the first three iron slits. The fourth slit is twice as wide as the others and houses a strip and a pad layer. Pad layers are inserted in the remaining five slits. Behind the iron is a second muon-box with three planes.

The signals of consecutive pads are added (5 inner + 6 outer layers) providing two–fold energy sampling in depth. All wire- and strip-signals are read out digitally. Three dimensional space-points from tracks can be obtained in the three chambers equipped with strips. Table 12 lists some parameters of the LST detector.

4.1.2 Gas system

Due to safety requirements the chambers are operated with a non-inflammable three component gas mixture of CO_2, argon and isobutane with relative volume fractions of 88 %, 2.5 %, and

Total size	4000 m^2
Nr. of profiles	13000
Nr. of wires	103000
Nr. of strips	28700
Nr. of analog channels	3888
Angular coverage	$6° \le \theta \le 172°$

Table 12: The LST detector.

9.5 %. The total gas volume amounts to 36 m^3. Different parallel circuits supply the detector with gas. The flow in each branch can be adjusted with needle valves and is measured with computer readable flow meters. 192 branches are used including some spare and test branches. The number of chambers connected serially was chosen such that the total gas volume per branch does not exceed $\approx$ 200 l. The gas composition, in particular the isobutane content, is controlled by two monitors. The gas flow is stopped and the HV is switched off if the fraction of isobutane is outside the range 8.5 % to 9.9 %

The gas quality is also monitored by two LST chambers equipped with a ^{90}Sr source, one in the incoming and one in the outgoing gas flow. The pulse height spectra of these chambers allow the monitoring of the gas composition and the HV regulation.

4.1.3 High voltage system

Five high voltage crates [112] with a total of 200 independent HV channels are used. Each channel supplies between 20 and 110 profiles. Chambers within one gas circuit are connected to the same HV channel. A passive distribution system allows to disconnect each single profile from HV in case of problems. All switches are computer readable, such that the HV configuration of each single 8–fold profile can be stored in a database.

Two different reference voltages can be applied to the detector. One is selected to be well below working conditions at $V_1 = 3000$ V. This setting is activated during unstable beam and injection conditions. The normal operating voltage is set to $V_0 = 4500$ V at normal pressure. Since the charge gain of streamer chambers depends on the pressure we adjust the high voltage accordingly. The gain variation amounts to $dQ/Q = -1.73\,\%\, dP/\mathrm{hPa}$. The high voltage V_0 is automatically adjusted by +2.75 V/hPa. In Hamburg one observes pressure changes of up to $\approx$ 6 hPa/h, and total variations of 80 hPa are possible.

Other relevant parameters such as temperature are monitored. They remain constant over long periods. The currents of all HV channels are constantly monitored. If a channel draws more than 5 μA, the corresponding voltage is automatically reduced until this current is below 5 μA. Channels are switched off, if this limit is exceeded for more than one minute.

4.1.4 Readout system

The readout of the analog information is incorporated as part of the LAr calorimeter and is discussed in Section 3.4. A digital readout system was developed for the wire- and strip-readout. Each wire (strip) is connected to a comparator, a synchronization circuit and a digital pipeline. The wire signal is digitized according to a computer adjustable threshold, synchronized with the HERA bunch crossing frequency and fed into a digital pipeline which has a depth of 32 steps corresponding to a total storage time of ≈ 3.1 μsec.

The front-end logic for eight data channels has been integrated in a gate array [113]. The leading edge of the input signal clocks the first flip-flop of a dead time-free synchronization circuit. The synchronized data patterns are buffered in a pipeline register. As soon as a trigger is accepted, the filling of pipelines is stopped. By means of a remotely controlled signal it can be decided whether the data pattern of one time slice, or the logical OR of two adjacent time slices is read out. This is necessary since the signal propagation within the chambers can exceed 96 ns, the time between two bunch crossings. In addition the eightfold OR of the stored data pattern is clocked into a separate flip-flop of the readout chain providing a signal for trigger purposes.

The electronics for 16 channels is housed on a readout card which is directly mounted onto the streamer chamber layers. This allows for early digitization and thus provides high noise resistance and a significant reduction in the number of cables needed. Multiple readout cards can be daisy chained. A layer of chambers is read out serially. The readout chains of a maximum of 24 layers are connected to special VME-based readout controllers (ROC) which provide zero suppression, data encoding, and submit all relevant steering signals to the readout cards.

Upon arrival of the first level trigger (L1), the ROCs start to collect the data from the electronics. The absolute position of the data corresponding to the triggered event within the front-end pipelines depends on the decision time of the trigger and the distance between the central trigger logic and the respective chambers. Due to the physical dimensions of the detector the delay is different for different areas.

One ROC serves up to 12300 digital channels corresponding to 24 chamber planes with 512 channels each. Since we operate 64 of these ROCs simultaneously less than 300 μs are needed to collect all data.

The architecture of the local DAQ environment is given in Figure 42. The VME crates are distributed in five clusters around the detector. The readout of these units starts after a second level trigger (L2). VME processors collect the data which are then stored locally. The data of up to 20 events can be stored before they are delivered to the central H1 data acquisition system.

4.1.5 Track reconstruction

The track reconstruction uses 16 wire, 5 strip and 11 pad layers, the latter being combined into 2 towers. The wires measure up to 16 points in the so-called 'wire plane' and the strips up to 3 points in the perpendicular 'strip plane'. The resolution for wire and strip hits is 3-4 mm and 10-15 mm respectively. The pads define coarse areas in space with a precision of about 10 cm.

The pattern recognition starts with the 16 wire layers. Track segments are parametrized by straight lines. To get curved track candidates several segments are connected. Then the pattern recognition selects track segments in the strips which have a matching wire track candidate. These matching wires and strips are then combined to a three dimensional track. In case of ambiguities the pad information is used to resolve them. The combination which fits best to the pads in space and amplitude (analog pad charge divided by number of wires hit) is chosen. The towers are then assigned to their matching wire and strip combination.

Due to crosstalk along the wires usually more than one pad gets a signal. With the centre of gravity of the pad charge the coordinate along the wires can be measured for both towers with an accuracy better than 10 % of the pad size. With these two additional points a direction in the strip plane can be determined even for very short tracks.

The magnetic field $\vec{B}(\vec{r})$ varies strongly inside the iron plates and in the gaps. The energy loss in one plate is on average 80 MeV for muons at perpendicular incidence. The track fit uses an average magnetic field for each plate and gap and performs a least square fit simultaneously to wire, strip and tower readings. The effect of the energy loss is accounted for by an iteration procedure.

4.1.6 Performance

During operation typically 0.1 % of the digital channels (wires, strips) are noisy and $1-2\,\%$ are dead.

Calibration data were taken during cosmic runs. One result is the efficiency of the chambers, which is shown in Figure 43. It agrees well with the expected values. Figure 44 shows the number of wires and strips per event for events triggered by the muon system. The wire data show a signal starting at a multiplicity of 13 which is roughly the mean number of wires expected for single penetrating muons with a plane efficiency of 80 %.

With cosmic muons the chambers of all modules have been aligned to each other with an accuracy of a few mm. In the barrel region cosmic muons can be used to determine the reconstruction efficiency by extrapolating jet chamber tracks. Geometrical acceptance limits this efficiency to 89 % in the plateau region above the threshold of 2 GeV as shown in Figure 45.

4.2 Forward muon spectrometer

4.2.1 General description

The purpose of the forward muon spectrometer is to measure high energy muons in the range of polar angles $3° \leq \theta \leq 17°$. The detector consists of drift chamber planes mounted on either side of a toroidal magnet. The design aim was to measure the momenta of muons in the range between 5 GeV/c and 200 GeV/c, the lower limit being given by the amount of material the muons have to penetrate and the influence on the momentum resolution of the multiple Coulomb scattering in the magnet iron. The upper limit is set by the magnetic field strength of the toroid together with the spatial resolution of the drift chambers. The expected momentum resolution at 5 GeV/c is 24% and deteriorates slowly to 36% at 200 GeV/c. Muon momenta below 5 GeV/c are measured in the forward tracker.

Figure 46a shows schematically the detector arrangement and the toroid magnet. The latter is described in Section 3.4 of reference [1]. The drift chamber planes, which increase in size from about 4 m diameter for the first detector plane to 6 m diameter for the last, are all divided into octants of individual drift cells mounted on Al-frames. The orientation of the drift cells is such that four of the planes essentially measure the polar angle (θ) and thereby provide the momentum of the traversing muon while the remaining two measure the azimuthal angle (ϕ). Each plane consists of a double layer of drift cells staggered by half a cell width (Figure 46b). This arrangement enables the resolution of left-right ambiguities and also the determination of t_0 as will be explained below. The total number of drift cells is 1520.

4.2.2 Chamber design

All drift cells have a rectangular cross-section with a depth of 2 cm, a width of 12 cm and lengths between 40 cm and 240 cm. With a central sense wire the maximum drift distance is 6 cm. The cells have 50 μm thick Nichrome wires except for the inner short cells where the diameter is 40 μm. For cells longer than 1.5 m there is a wire support in the middle. More details can be found in reference [114].

The chamber signals are amplified, digitized and read out using the same components as all other drift chambers within the H1 detector (see Section 2.4).