run the master processor operates asynchronously, waiting for an event to be signalled by the trigger processor, and then polling the front end processors until the complete event is ready to be built. The events are not buffered or processed by the master processor.

A monitoring crate provides access to the readout branch for chamber specific control and monitoring systems. A small fraction of the event data can be passed to the monitoring crate for local monitoring, especially that which requires raw data that might be unavailable in the CDAQ monitoring systems. Data is collected from a dedicated memory in the master crate using a differential VSB extension [34] – the VIC8251 connection is not used for technical reasons. Data may also be fed back from the monitoring system into the data stream, to allow important slow control information (e.g. HV, currents) to be recorded together with the event.

The drift chamber readout uses processors of the Motorola 68000 family throughout. These CISC processors are relatively easily programmed at the native instruction level, and all the readout code was written in assembler. By splitting the workload between many processors each fulfilling a specific task it has been possible to avoid the use of an operating system on any of the readout processors. This has minimised response times and maximised performance.

2.5 Proportional chambers

Between 5° and 175° the solid angle seen from the interaction region is completely covered by multiwire proportional chambers. Six independent planes in the forward direction, four in the central and also in the backward direction serve three different functions: to deliver a fast timing signal with a time resolution better than the separation of two succeeding HERA bunch crossings, to provide moderately accurate space points for charged particle track reconstruction at the first level trigger and lastly to add an accurate track element in the backward direction, where the drift chambers fail to provide enough space points.

The planar forward chambers (FWPC) are interspaced between the driftchambers of the FTD described above and are exposed to high particle rates increasing towards the beam pipe. Hence minimum overall thickness and minimal amount of material traversed, sufficient ageing prospects, and cathode pad size adapted to increasing rates near the beam pipe became the primary design criteria. These points do also apply for the two cylindrical chambers in the central region. The inner one (CIP) is closest to the interaction region and covers the largest solid angle. In order not to degrade the track reconstruction of the surrounding drift chambers, the CIP and its outer partner (COP), were fabricated with low mass materials and a narrow active gap. Since the main purpose of the FWPC, COP and CIP is to provide space points for the first level trigger, a pad segmented cathode readout was chosen with graphited surfaces as in other chambers built for high rates [35, 36]. From the reconstructed tracks the event vertex can be deduced and other detector data such as calorimeter and muon information can be validated. Since the trigger logic requests three space points per track, spurious background hits from uncorrelated noise and synchrotron radiation are removed.

In the backward direction the reconstruction of the scattered electron in low momentum transfer events calls for an accurate track segment. This is given by the signals from the four differently oriented anode wire planes of the backward chamber (BWPC). Several wires can be combined for triggering purposes. Standard planar chamber construction techniques sufficed here, since more than one radiation length of electronics and cables from the central tracker separate the BWPC from the interaction region. The BWPC covers the front surface of the backward electromagnetic calorimeter (BEMC) and hence also serves to discriminate electrons and photons.

The properties of all four chamber types are summarized in Table 5. The front end electronics and readout system is identical for all chambers.

	unit	CIP inner/outer	COP inner/outer	FWPC # 1/# 2/# 3	BWPC
active length $\Delta z/\Delta r$[3]	mm	2190	2172	583	515
active zone starts at z/r[3]	mm	-1125	-1107	167	135
mechanical length $\Delta z/\Delta r$[3]	mm	2254	2262	665	597
total length $\Delta z/\Delta r$[1,3]	mm	2467	2360	665	708
thickness $\Delta r/\Delta z$[3,6]	mm	21.5 (25)	30 (34)	40	52 (60)
chamber starts at z/r[1,3]	mm	-1376	-1270	135	110
position of first anode r/z[3]	mm	157/166	501/514	1451/1874/2297	-1423
number of anode planes		1	1	2	4[5]
number of wires		480	1574/1615	724	2496
wire separation	mm	2.1/2.2	2.0	2.5	2.5
gap width	mm	3.0	4.0	4.0	4.0
number of cathode pads		480	288	384	
cathode resistivity	k$\Omega/\square$	$\approx$400	$\approx$ 200	$\approx$300	$\approx$400
length of pad $\Delta z/\Delta r$[3]	mm	36.6	120	13 to 54[4]	
width of pad $\Delta\phi$	°	45	22.5	45 (22.5)[2]	
anode wire tension	N	0.63	0.60	1.5	0.98
plateau length	V	200/250	200	300	200
plateau starts at	V	2425/2375	2900	1900	2800

Table 5: Proportional chamber parameters. The separate columns for CIP and COP refer to the two planes, for the FWPC to the whole module containing two planes.
[1] Inclusive preamplifiers; [2] only for the four outermost of the 20 radial pads;
[3] first coordinate for CIP and COP, second for FWPC and BWPC; [4] width increases with radius, $\Delta r_i = 0.0782 r_i$, where r_i is the inner radius of the pad; [5] the anode wire of each successive plane are rotated by 45°; [7] in active zone (and at end flanges).

2.5.1 Forward proportional chambers (FWPC)

Each of the three chambers in the forward tracker volume consists of two wire planes interleaved with three cathode planes. The gap between the two adjacent cathode planes is 4 mm wide, as indicated in Figure 10. All chamber frames are made of glass fiber epoxy. To reduce the mass in the active area a laminated structure consisting of the following layers is used: 100 μm graphited mylar foil serving as cathode plane, 250 μm printed circuit board carrying 10 μm Cu readout pads, 3.3 mm Nomex [24] mesh, another 250 μm printed circuit board covered with 10 μm Cu for the strips leading from each pad to the preamplifiers on the chamber ends, a further 100 μm of graphited mylar foil in the central plane or aluminized mylar foil on the external planes for electromagnetic shielding. The graphite layers are produced by spraying a mixture of DAG 5466/DAG 213 [37] at 5 bars giving an initial surface resistivity of 1 M$\Omega/\square$, which was reduced to 300 k$\Omega/\square$ by polishing. Each chamber is strengthened by a backplane, 12 mm thick, with two layers of 250 μm glass fiber epoxy sandwiching 11.5 mm Nomex. The overall thickness is 1.7 % of a radiation length. The mechanical tensions of the wires and the foils are supported by 24 and 8 axial rods on the external and internal frames, respectively. The anode planes contain gold plated tungsten wires (Ø 25 μm) spaced by 2.5 mm. They are crimped on pins fixed on the frames. Each wire is connected to the following one through 1 MΩ resistors and to ground through 330 nF capacitors. Groups of 15 wires are connected to separate HV lines, which allows degrading of malfunctioning sectors if necessary. The cathode pads are ring shaped and cover an azimuthal angle of $\pi/8$ each, except for the four outermost of the 20 rings where they cover $\pi/16$. The radial pad width increases with radius in geometrical progression from 18 to 37 mm. Two consecutive cathode planes are offset by one half of a ring, such that the effective polar angle resolution is halved: $r_{min,i+1} = r_{min,i} \times 1.0382$ with $167.5 \leq r \leq 750$ mm. The Pluto gas mixture (see Table 7) was chosen, because the FWPC share their gas volume with the forward drift chambers and transition radiation detectors.

A track crossing all three or at least two modules of the FWPC has to fall into the polar angle range $6.6° \leq \theta \leq 18.0°$ or $5.1° \leq \theta \leq 21.6°$, respectively. For such tracks an effective timing resolution of 20 ns (FWHM) and 47 ns (base width at 10 % of the maximum) was measured using H1 data, well below the required resolution to separate two bunches.

2.5.2 Central proportional chambers

2.5.2.1 CIP The laminar structure of the CIP called for special construction techniques which are described in detail in reference [38].

The double layer of chambers consists of three concentric cylinders. During construction each chamber cylinder was formed on a steel mandril milled to a precision of 25 μm over the full length. The innermost layer of the first cylinder, a 25 μm thick Al-foil provides the electromagnetic shielding. The next layer – 2 mm thick Rohacell foam [14] glued onto the Al-foil with 20 g/m^2 epoxy-glue [39] – gives the chambers the necessary rigidity. The Rohacell surface was polished, and a second 25 μm Al-foil glued to it served as the inner cathode. After cutting the cylinder to the right length the Al-foils were connected to Cu-foils, at the ends and the glass fiber epoxy [6] end flanges were added. These carry the printed circuit boards for the anode wires, which are supported further by glass fiber epoxy rings at 1/3 and 2/3 of the chamber length. The active gap is 6 mm wide. The anode wires (gold plated tungsten, Ø 25 μm) were transfered to the axially prestressed cylinder from planar frames.

The middle cylinder forms the outer cathode of the inner chamber and the inner cathode of the outer chamber. Here the innermost layer, a 20 μm Kapton foil is coated with high resistive graphite (400 k$\Omega/\Box$) on one side and 0.5 μm Al on the other side. The Al layer is segmented into pads on which the induced charge on the cathode is collected. The graphite layer in front guarantees a fast disappearance of the accumulated ion charge. This has the advantage, that the readout wires of the pads can be mounted outside the gas volume. After several tests on prototypes [38] the graphite layer in the final chamber was produced by spraying a mixture of DAG213, DAG305 [37] and isobutylmethylketon (IBMK) in a ratio of 20 : 1 : 7 onto the Kapton foil with 3 bar. The cathode foils are again backed by 2 mm Rohacell. The readout wires (150 μm Al) are embedded into 250 μm deep grooves in the Rohacell running along the $z-$axis from the chamber end ($-z$ side) to a hole centered over the pads. The wires were contacted onto the pads with silver paint and soldered at the flange end. Another 20 μm thick Kapton foil with Al-coating is glued onto the Rohacell, which forms together with the wires a wave guide of $\sim 70\ \Omega$ impedance. The Kapton foil again backed by 1 mm Rohacell with a polished surface is covered by another 25 μm Al foil serving as the cathode for the outer chamber. End flanges and connections are similar to those of the first cylinder and the sequence of layers for the third cylinder is identical to that of the second.

Gas sealing is provided by two O-rings at the end flanges (2 mm Ø). The overpressure in the chambers has to be kept small and needs to be monitored carefully in order not to distort the gap. The two chambers have independent gas distributions and are rotated by $\pi/16$ in ϕ with respect to each other, thus halving the eightfold segmentation of each chamber at the trigger level by requiring coincidence of two planes. In z there are 60 pads of 36 mm width in each ϕ sector.

With the gas mixture given in Table 7 the single pad efficiency measured in a test beam was 99 %, while at HERA 94 $\pm$ 2 % was measured with extrapolated jet chamber tracks. From the measured pulse height distributions the gap variations for this light chamber were deduced to be less than 0.2 mm. The measured test beam time resolution (FWHM 21 ns) compares well with the results at HERA. This result converts into a 2 % probability to register a given pad with the wrong (neighbouring) bunch crossing. The probability for crosstalk, i.e. the probability to register signals also in neighbouring pads in z and ϕ and the inefficiencies across the pad boundaries are discussed in detail in reference [38]. The average number of active pads for crossing angles larger than $\theta = 40°$ in a test beam (1.4) compares well with what is observed at HERA.

2.5.2.2 COP The construction of the COP follows closely that of CIP in those aspects concerning the sandwich structure (see Figure 12). Steel mandrils machined to a precision of 60 μm and appropriate to the larger chamber radii were used. To improve the stability of the sandwich structure, the thickness of the core material (Rohacell) was increased to 4 mm. The graphite cathodes (7 m^2 area per chamber) are produced with a screenprinting technique using a resistor ink solution, rather than spraying . The ink [40] has a resistivity of 170 K$\Omega/\Box$ for a 15 μm layer and was diluted with a solvent monobutylic ether of ethylene glycol in a ratio of 1 : 3. A surface resistivity of 200 K$\Omega/\Box$ was obtained after polymerization at 120 °C during 1 hour. The cathode pad structure is provided by gluing patches of 25 μm Kapton coated with 1 μm Cu to the back side of the graphite cathodes, giving an 18–fold segmentation in z and 16–fold segmentation in ϕ. The cathode layer is backed by 3 mm Rohacell, in which 50 μm diameter Cu wires are embedded. A 25 μm Kapton foil coated with 1 μm Cu put on top of the previous layer constitutes with the copper wires the transmission line that carries the chamber signals to the $-z$ end of the chamber. This layer is then backed by 2 mm Rohacell. The Vetronite (G10) end flanges of the chamber support the printed circuit boards to which the anode wires ($\approx$ 1600 per chamber) are soldered and assure the 8 mm chamber gap size. They form the only rigid structure to which the gas distribution and preamplifiers are connected. The three cylinder sandwiches are assembled in vertical position. Pulse height measurements showed that the gapsize variation is of the order of 0.3 mm [41].

Despite its three times larger radius the COP is only moderately thicker than CIP (0.18 % radiation length instead of 0.14 %). The efficiency plateau is reached at 500 V above the CIP plateau with the same gas mixture, a consequence of the larger gap. While in test beams CIP and COP behaved similarly, at HERA the noise level in COP is slightly higher due to more difficult grounding. This requires a higher threshold setting and leads to a typical efficiency of 92 $\pm$ 2 %. The timing resolution is similar to that of the other chambers.

2.5.3 Backward proportional chamber (BWPC)

The BWPC is equipped with five graphited cathode planes (50 μm Mylar foil) and four anode wire planes. It is the only chamber in H1 in which the cathodes are not segmented and the anodes are read out. The graphite coating was fabricated with the same technique as described for CIP. The wires and the foils are stretched between a 23 mm wide inner and a 67 mm wide outer ring of glass fiber epoxy (G10). These rings are 4 mm thick and sustain the active gap of 8 mm per chamber, as indicated in Figure 13. The wires are strung every 2.5 mm, but signals from two neighbouring wires are fed to one preamplifier. The wire orientations are vertical, horizontal and $\pm 45°$ for the four layers. Gas sealing and structural support for the assembly is provided by G10 front and back planes of 10 mm thickness milled down to 6 mm in the active zone. The latter starts at an inner radius of 135 mm and ends at 650 mm, while the whole chamber occupies the region betweenn $r = 110$ mm and $r = 818$ mm. The BWPC therefore covers polar angles of $174.5 \geq \theta \geq 155.5°$. The space points given by the BWPC contribute 0.5 mrad to the angular resolution, of the same order as the multiple scattering in the material in front of it. For high energy electrons an efficiency of 87 % per plane was measured from extrapolated CJC chamber tracks. When requiring three out of four planes to be hit in coincidence with the BEMC an efficiency of 98 % is obtained.

2.5.4 Proportional chamber electronics and readout

Preamplifier		Amplifier–Shaper	
Differential gain	65 nV/e	Max. differential gain	400
Rise time (10–90)%	2 ns	Rise time	9 ns
Fall time (10–90)%	20 ns	Pulse width (FWHM)	16 ns
Input impedance	64 Ω	Max. output voltage	3.2 V
Output load	2×50 Ω	Overload recovery:	
Dynamic range	± 300 mV ($\approx 10^7\, e$)	$V_{in} < 5 \times V_{in,sat}$	70 ns
Power supply	± 3.5 V (22 mW)	$V_{in} = 30 \times V_{in,sat}$	170 ns
Size	$25 \times 10 \times 2$ mm^3	Power supply	+5, -5.2 V (320 mW)
		Size	$36 \times 3 \times 6$ mm^3

Table 6: Characteristics of the MWPC preamplifier and amplifier–shaper.

A schematic picture of the frontend electronics is shown in Figure 14. The cathode pad signals (CIP, COP, FWPC) and anode wires (BWPC), respectively are preamplified directly on the chambers. A differential signal is then transmitted through a 35 m long cable to the electronic trailer. Each cable contains 16 signal pairs and is connected to a receiver card containing shaping amplifiers, followed by discriminators with computer controllable thresholds. The characteristics of the preamplifier-shaper chain are listed in Table 6. The overall gain can be adjusted to chamber pulse height between 1.3 μV/e and 26 μV/e by means of a resistor on the receiver card. A typical equivalent noise charge is about 3800 e, for a chamber capacity of 60 pF.

The digitized signals are synchronized with the HERA clock and stored in a pipeline constructed from the same gate arrays as used in the muon system (see Section 4.1.4). Upon a first level trigger decision (L1-Keep), the pipeline clock is stopped. A second level trigger decision (L2-Keep) then initiates the data readout. The synchronized pad signals are furthermore made directly accessible to the $z-$vertex and forward ray trigger (see Section 5.3.1.3 of reference [1]). Test registers allow controlling the readout and trigger chains.

The MWPC readout system, an independent branch (# 7) of the H1 data acquisition system (see Figure 22 of reference [1]), is responsible for reading 3936 channels, originating from 270 receiver cards in 15 crates, and some decision data from the two first level triggers. In addition to the frontend crates, the system consists of two standard VMEbus crates and one STC crate [33] in a configuration common to all H1 subsystems (see Section 7.2.1 of reference [1]).

The frontend crates are equipped with a customised 'EasyBUS', which is essentially a simplified 16 bit wide VME bus with a 64 kWord address space lacking any interrupt capabilities but with added analog and ECL signal lines. The latter are used to distribute the clock and L1-Keep signals. The analog lines allow measuring the digitization thresholds loaded to the discriminators through an ADC located on a crate controller (CC) card. The primary task of the CC's is however to connect the crate to a branch driver card (BDC) residing in the master VME crate. The BDC-CC combination maps the EasyBUS address space into the VME frame [42].

Each BDC is directly connected to the STC and contains a DMA (direct memory access) controller and a 4 Kbyte deep FIFO (first in, first out) buffer. An L2-Keep signal can thus initiate a frontend data transfer to the master crate without processor intervention. The maximum transfer speed is 4.5 Mbyte/s. Each of the six BDC's installed in the MWPC area can control eight frontend crates. The latter are grouped into pairs to make use of the 32 bit wide data path of the VME bus. To optimise readout speed, between two and six crates are connected to one BDC.

The first order dead time is determined by the front-end transfer to the BDC as long as the BDC FIFO are not saturated. The saturation rate is given by the average time spent by the data acquisition processor per event. Details of the data acquisition program are available in references [42]. An average time of 4.2 ms per event is needed. This corresponds to an average of 237 hits in 10 bunch crossings.

2.6 Gas systems

To operate the nine different tracking detectors nine separate gas circuits are necessary, with different gas mixtures, flows, and demands on purity and overpressure control. For the forward chambers and CJC closed circuits are used while CIZ, COZ, CIP, COP and BWPC are flushed with premixed gases in open circuits. The main parameters of the gas systems are given in Table 7.

Detector	Gas volume	Gas mixture + additives: volume ratio	Pressure relative to atmosphere		Flow rate		System
			typ.	max.	typ.	max.	circuit
	[l]	[%]	[hPa]		[l/min]		type
Planars+ FWPC	$\sim$900	$Ar/C_3H_8+C_2H_5OH$ (90/10)+1	0.15±0.10	1	1.3	3	I closed
Radials	$\sim$700	Phase I: Ar/C_2H_6 (48/52) Phase II: $Xe/C_2H_6/He$ $+C_3H_7OH$ (20/40/40)+1	0.15±0.10	1	1.0	2	
Radiators	$\sim$500	He/C_2H_6 (60/40)	0.25±0.10	1	0.1	1.5	open
CJC1	$\sim$1140	Phase I: $Ar/CO_2/CH_4$ (89.5/9.5/1)	1.5±0.5	5	1.5	3	II closed
CJC2	$\sim$3080	Phase II: $Ar/C_2H_6+H_2O$ (50/50)+0.5	1.5±0.5	5	4.5	9	
CIZ	$\sim$55	$Ar/C_2H_6+H_2O$ (70/30)+0.2	0.15±0.10	1	0.1	0.6	III open
COZ	$\sim$240	$Ar/C_2H_6+C_3H_7OH$ (48/52)+1	0.15±0.10	1	0.2	0.8	
CIP	$\sim$30	Ar/C_2H_6/Freon12$+H_2O$ (49.9/49.9/0.2)+0.2	0.15±0.10	1	0.07	0.6	
COP	$\sim$150	Ar/C_2H_6/Freon12 (49.9/49.9/0.2)	0.15±0.10	1	0.1	0.6	
BWPC	$\sim$120	Ar/C_2H_6/Freon12 (49.9/49.9/0.2)	0.15±0.10	1	0.1	0.6	

Table 7: The different circuits of the gas systems.

2.6.1 Gas circuits

The simplified diagram of the gas circuit of the planar chambers shown in Figure 15 illustrates the typical features of the gas systems. The system is distributed over three levels, the supply outside the H1 hall, the control room on the first underground floor and finally the distribution rack on top of the electronics trailer near the detector. At the latter point the gas inlet flow for each detector is adjusted by mechanical flow meters and for some chambers split into several streams for further distribution as shown in Figure 15. The static pressure of chambers relative