Apart from a narrow strip near the cell walls the chamber efficiency was measured to 98 % in test beams at PSI [16]. From test beam data the resolution was found to be $\sigma_z = 320\ \mu$m independent of the drift distance and the crossing angle in the range $10° < \theta < 110°$. These results could be confirmed with cosmics ray data, where central jet chamber tracks were extrapolated into the z-chambers and then linked to the corresponding track elements. The average deviation from a straight line fit (in the $r - z$ plane) is $\sigma_z = 260\ \mu$m for CIZ internal track elements and 400 μm for linked tracks. For the $\phi-$projection a resolution of 2.4 % of the wire length was measured. Double pulses can be resolved, if their separation exceeds 90 ns, which converts into 4.6 mm spatial separation in z [16].

2.2.2 COZ

This chamber was also built on a Rohacell body with the cross-section of a regular 24-edge polygon (Figure 3), but resting on a cylinder of carbon fiber reinforced plastics. The Kapton foils with field shaping copper strips were glued to the Rohacell surfaces. Guided by a mechanical positioning device the wire supporting rods (G10 with Cu strips, double sided) were placed and soldered to the Kapton foil. Between these rods planar cathodes were introduced made of G10/Cu with holes to enable the gas flow through the chamber. The top cover of the drift cell structure consists of a Kapton-Rohacell sandwich which is fixed at the cathodes. The chamber has a cylindrical shape due to its G10-Cu gas cover held by the endflanges. Further details can be found in references [17, 20]. Figure 8 shows a schematic view of the COZ. The dead zones for the wire readout are distributed in azimuth which allows a corresponding distribution of the preamplifiers at the end flanges and minimises the dead area of the chamber. The anode signals are transmitted by twin readout lines (signal-ground signal, length 20 to 120 cm) from the wire ends to the preamplifiers on both chamber ends.

Each drift cell is 24 mm high, the maximum drift length is 46 mm which limits the drift time to about 1 μs. Each cell has four sense wires (Stablohm [18], Ø 48 μm, 0.6 kΩ/m) in the symmetry plane of the cell and three pairs of potential wires (CuBe, Ø 127 μm). The wire feedthroughs in the supporting rods are kept in their nominal position to about 30 μm (σ). No wire stagger is implemented. Mirror tracks can be removed in the analysis since they do not point to the vertex.

The COZ is typically operated with a cathode voltage of 3000 V, a potential wire voltage of 2250 V and field gradient of 82 V/mm. For the gas mixture listed in Table 7 this gives a drift velocity of 48.5 mm/μsec, as determined from tracks crossing the sense wire plane and the cathode plane, respectively.

Inefficiencies along the cell walls and other performance parameters were studied in test beams (3 GeV electrons at DESY and low energy pions and electrons at PSI, see references [21, 20]). Apart from a small region near the sense wire feedthroughs the efficiency was determined to be 98 % over the full drift cell. For a 90° crossing angle the resolution measured at HERA is about 200 μm, deteriorating to 500 μm for low crossing angles. The azimuthal angle is determined by charge division to an averaged accuracy of 7.2 °, i.e. 2 % of the wire length. Double pulses can be resolved if their separation is larger than 70 ns which corresponds to 3.5 mm distance. For a discussion of the optimum method to resolve double tracks and a comparison of different algorithms for (Q, t) analysis we refer to [20, 21, 22].

2.3 Forward tracking detector

The forward tracking system is designed to provide an accurate measurement of charged particles in the forward direction (momentum resolution $\sigma_p/p^2 < 0.003$ GeV^{-1} and track angular resolution $\sigma_{\theta,\phi} < 1$ mrad), track information on individual particles within jets, electron identification by means of transition radiation detection and a fast forward ray track trigger. Details about track finding and fitting can be found in [23].

The layout of the FTD is illustrated in Figures 9 and 10. Key parameters are listed in Table 3. The drift chambers have different wire geometries - the planar ones contain parallel wires whereas the radial ones have wires radiating outwards from the beam pipe – all wires being strung perpendicular to the beam direction. The planar module consists of three drift chambers, each four wires deep in z and rotated at 60° to each other in azimuth. It is located closest to the central tracker in each supermodule, since its homogeneous spatial precision in x and y is most suitable for linking to tracks in the center. For practical reasons the FWPC (Section 2.5.1) is mounted directly behind the planar drift chambers in order to share the same gas mixture and maximise the geometrical trigger efficiency of the FTD. After the FWPC the particles traverse a transition radiator consisting of 400 polypropylene foils contained in its own gas volume. The transition radiation photons pass through a thin mylar window and are detected in the radial chamber which produces up to 12 accurate space points from ionization drift timing and charge division. To improve double track resolution the second and third radial modules are rotated by 3.75° and 2.5° (1/2 and 1/3 of a wedge) relative to the first. The interleaving of planar and radial chambers provides the optimum lever arm for momentum measurement.

The individual chambers were assembled and tested separately. The components for a single supermodule were installed into a three section tank consisting of aluminium outer cylinders ($\O_{max}$ = 1700 mm) and glass free carbon fiber inner cylinders ($\O_{min}$ = 243 mm, 4 mm thick, lined with Al foil), each tank section forming an independent gas volume and electrically isolated environment. Each chamber is bolted to the rigid central U-shaped outer cylinder using a set of precision dowels for alignment. Assembly was carried out on high quality surface tables with dimensional tolerances kept to $< 30\,\mu$m throughout the build sequence. After commissioning each supermodule on a cosmic ray test facility the three supermodules were then bolted together, separated by thin gas tight Kapton windows, and the end faces closed with stiff plates made from a sandwich of 1.2 mm thick Al alloy and 17.6 mm thick Nomex honeycomb [24]. The final alignment of the whole FTD was measured using cosmic rays after installation into the H1 experiment. Water at constant temperature (± 1 °C) is circulated around each tank section through copper pipes in order to maintain dimensional stability and provide cooling for the preamplifiers. As well as maintaining the relative alignment of the tracker elements and support for the various services – water, gas, cables, preamplifiers, position monitors etc., the tank provides an electromagnetically sealed environment and serves as the common ground for the chambers. The HV and signal cables access the tracker volume via the outer cylinder using hermetically sealed feedthroughs where they are grounded. The HV cables are also filtered before entering the tank.

Three different gas mixtures are used, two working gases for the chambers and one purge gas for the transition radiation (TR) volumes. Gas is fed into each supermodule volume via the U-shaped channels in the outer cylinder, two feed pipes and one pipe for local pressure sensing, a total of nine pipes per supermodule. Gas tightness is maintained by rubber O-ring seals at the outer and inner flanges. The gas is supplied at atmospheric pressure from three computer controlled closed loop gas circuits (see Section 2.6) which maintain gas purity and provide the accurate pressure control, $\pm 10\,\mu$bar required in order to prevent damage to the fragile TR windows. During HERA operation the oxygen level in all volumes has been kept to < 50 ppm.

The whole tracker is mounted on four insulated feet and rests on the cryostat rails in stress-free condition. It is electrically isolated from the central tracker and the cryostat.

Parameter	unit	Radials	Planars
number of cells per supermodule		48	32
inner (outer) active radius	mm	150 (750)	$\approx$ 150 (750)
total number of sense wires (per cell)		1728 (12)	1152 (4)
sense wire diameter (resistance)	μm (Ω)	50 (450)	40
sense wire material		Stablohm[1]	W (Au plated)
sense wire spacing Δz (stagger)	mm	10 (0.28)	6 (0.30)
sense wire tension	N	1.75[2]	1.20[2]
total number of grid wires (per cell)		1584 (11)	2880 (10)
grid wire [Cu-Be(2%)] diameter	μm	125	125
grid wire tension (surface field)	N (kV/cm)	2.80[2] (170)	4.00[2] 135)
sense voltage	V	+2228	+1575
bulk (grid) field gradient	kV/cm	1.2 (-6.9)	1.0 (-5.0)
maximum drift distance ($B = 0$ T)	mm	50	28
drift velocity ($B = 0/1.14$ T)	mm/μs	$\sqrt{3} \times 37/37$	43.5/42
Lorentz angle ($B = 1.14$ T)	$^\circ$	45	41.8
z planar (x), module 0/1/2 [3]	mm	1324.4/1746.4/2168.4	
z planar (u), module 0/1/2 [3]	mm	1367.0/1789.0/2211.0	
z planar (v), module 0/1/2 [3]	mm	1409.6/1831.6/2253.6	
$z-$ radial, module 0/1/2 [3]	mm	1593.0/2015.0/2437.0	
$\sigma_{r\phi}(\sigma_r)/\sigma_{x,y}$ from track segments	μm (cm)	180 – 200 (3)	150 – 170
double track resolution	mm	2	2

Table 3: Forward tracker drift chamber parameters and positions.
[1] alloy from ref. [18]; [2] 60 % of the limit of proportionality; [3] position of first wire in plane.

2.3.1 Planar drift chambers

Each chamber is constructed as a self-supporting module containing 32 drift cells of identical rectangular cross-section with wire lengths between 460 mm and 1410 mm as shown in Figure 10. The chamber walls are formed from two circular discs with an outer diameter of 1.57 m and a central aperture of 280 mm diameter. They are composed of a low mass composite of Fibredux skinned Nomex honeycomb 3.4 mm thick, manufactured to be parallel and flat to within 100 μm. A 0.8 mm thick double sided printed circuit board carrying the drift field forming strips and voltage bus on opposite faces is bonded onto one side of the honeycomb laminate. the drift cells are defined by parallel sets of copper clad PCB's, 0.8 mm thick by 32 mm high, mounted perpendicularly and bonded at 57 mm intervals into precisely machined slots in the honeycomb panels, resulting in a multiple box section structure of high mechanical strength and rigidity. The vertical PCB's constitute the cathode planes and define the maximum drift distance as 28.1 mm (for $B = 0$). Each cell contains four sense wires uniformly spaced in z and staggered alternately 300 μm each side of the median plane of the cell. Each sense wire is surrounded by four grid wires Cu-Be arranged on a 6 mm square matrix. Significant benefits arise from the double grid design including reduced cross talk, lower wire tensions, improved cell isochronicity, and reduced grid wire surface fields. All wires are crimped under tension in pins which are held in position by means of high precision extruded Noryl templates at each end of the cell. The principal source of error in the wire position (≈ 20 μm) arises from the inherent inaccuracies in the crimping technique. The cell ends are closed by PCB's containing electrodes which cleanly terminate the electrostatic field of the cell. Aluminium foils covering the outer surfaces and connected to the tank provide electromagnetic isolation between the individual planes. A set of precision dowels fix the relative orientation of each plane (to < 0.06 mrad), the orientation of the planar supermodule with respect to the FWPC and the planar chamber/FWPC combination with respect to the tank.

The cell electric field distribution is controlled by seven different voltages: the sense voltage defines the gas amplification, the central strip voltage affects the sense field homogeneity, four drift strips and the cathode voltages determine the field gradient. The grid wires are grounded. All voltages are supplied directly from the HV supplies, after suitable fan out, without the use of resistor chains at the chamber. Field optimization and chamber operation are considerably aided by the fact that the double grid geometry produces a strong decoupling between the sense field (gas amplification) and the drift field. The operating conditions of the chambers for the gas mixture given in Table 7 are listed in Table 3.

The outer end of each sense wire is AC coupled into a current sensitive preamplifier (two drift cells per preamplifier) and the signals transmitted via 40 m of 50 Ω coaxial cable to the FADCs. Pulse profile (Q, t) analysis in the front end data acquisition system yields one drift time coordinate measurement perpendicular to the sense wire and one pulse integral measurement. Resolutions achieved on $e-p$ data are typically $150-170\,\mu$m for the single point spatial resolution and < 2 mm for the double track resolution.

2.3.2 Radial chambers

The radial wire drift chambers cover 360° in ϕ with 48 separate sectors of 7.5° width. Each sector is a drift cell having 12 sense wires staggered alternately 287 μm each side of a plane which bisects the sector. The sense wires, which are all parallel within one of these cells, are separated by 10 mm. Between adjacent sense wires, and positioned on the plane which bisects the sector, are field wires parallel to the sense wires and half way between them. All these wires are supported by crimp pins. At the small radius end (r = 152 mm), the crimp pins are mounted in a cylindrical Noryl hub, and at the large radius end (r = 760 mm), in Noryl templates precision bonded into the cylindrical wall of the composite structure which contains the whole 48 cells of the radial chamber as one rigid unit. The structure of these radial drift chambers has been described in references [25, 26, 27].

The wedge-shaped drift cells are separated from each other by cathode planes which consist of voltage graded copper strips on each side of thin paper-epoxy material (PCB technology). The electrostatic field cage for each drift cell is completed by voltage graded shaped conducting strips bonded onto the plane inner surface of the composite structure (for the high z end of the wedge), and onto a complex window assembly, described below, which is affixed as a lid to the composite structure (for the low z end of the wedge).

Detailed design of this window, forming the plane surface of the radial chamber towards low z was determined by the requirement to detect the transition radiation (TR) entering the radial drift chamber. The X-ray component of TR produced by an ultra relativistic charged particle contributes to an enhanced track ionization, hence to enhanced charge collected on one or more of the sense wires, provided that all ionization deposited anywhere in the cell is collected onto the sense wires and not onto field wires. The window of the radial chamber is thus designed to be as X-ray transparent as possible, and to ensure maximum X-ray detection efficiency as close as possible to it inside the drift cell. Because of the imperfect nature of the field grading close to the V shaped strips, ionization deposited within about 2 mm of the window cannot be collected onto the first sense wire. Such a loss of X-ray sensitivity is significant at the TR entry (low z) side of the radial chamber, where most of the X-ray photons photo-ionize the chamber gas. For this reason the V shaped strips to create the drift field are of aluminium on mylar and are supported on Rohacell [14] spacers which position them 5 mm from the thin mylar window which isolates the chamber gas volume. The effect of this window assembly on the electrostatics is to move the drift field inhomogeneities out of the sensitive gas volume. Then at the mylar wall closing the gas volume the drift field is uniform and parallel to the surface, except directly opposite the sense wire. Charging effects on the mylar window are then minimal, and the ionization collection efficiency on the first sense wire is optimal right to the edge of the gas volume.

Because all the sense wires are in the radial direction, a coarse determination of the radial position of a track may be made from charge division if a wire is read out at both ends. However it is not physically possible to have preamplifier cards at the small radius end. For this reason the sense wires of one 7.5° sector drift cell are connected at the inner hub to the sense wires of another 7.5° sector drift cell, actually 105° away in azimuth, so that when sense wires are read out at the outer radius charge division is possible along this double length of radial wire. Current sensitive preamplifiers are at each end of these sense wire pairs, each channel of which drives approximately 40 m of cable to the FADC system. Pulse profile (Q,t) analysis gives the drift coordinate perpendicular to the sense wire plane, and two pulse integral measurements Q_L and Q_R from the two ends give the radial position by charge division.

The spacing in the z direction between the sense wires of the radial chambers, between the three modules, and the sets of planar drift chambers and the radial drift chambers may be seen from Table 3. Concerning the azimuthal position of the radial chambers, the plane which bisects a 7.5° sector cell (and about which the sense wires are staggered) is at $\phi = 3.75°$ in the first module, at $\phi = 7.5°$ in the second module and at $\phi = 6.25°$ in the third module. The resolution achieved with the 50 % argon, 50 % ethane gas mixture used so far is $150 - 200$ μm. The gas mixture which is intended to use for optimal detection of transition radiation is given in the following section.

2.3.3 Transition radiators

A passive array of polypropylene layers provides a sufficient number of dielectric interfaces for useful transition radiation (TR) X-ray emission. The dielectric constant, the layer thickness and the mark to space ratio of the polypropylene sheets determine the X-ray yield and the energy spectrum. For the values chosen the spectrum peaks around 6 keV for 20 GeV electrons. The interface between the TR and the radial wire drift chambers has been optimised for transmission of these X-rays. As described in the previous section the radial wire drift chambers are designed and operated both for optimal track point measurement and efficient X-ray detection. The combination of TR and radial wire drift chamber is designed for electron-pion discrimination, at the level of 90% electron acceptance with less than 10% pion contamination, up to 80 GeV for tracks passing through all three modules of the FTD. To achieve this, it is planned to operate the radial wire chambers with a gas containing xenon which has a high photoionization cross-section at 6 keV. A 20 % xenon, 40 % helium, 40 % ethane mixture satisfies the requirements of TR detection with acceptable charged track dE/dx ionization density, and also suitable drift velocity for the requirements of the drift chamber. Data taken with a radial drift chamber in a test beam at CERN have shown that the design discrimination between electrons and pions can be achieved with this gas [28, 29].

The assembly of polypropylene sheets is self supporting but is enclosed in its own gas envelope in order to isolate it from the gases used in the rest of the FTD. The helium-ethane mixture surrounding the polypropylene sheets is chosen to give the same partial pressure of helium as in the radial drift chamber. This is important because the interface is the thin mylar TR window of the radial drift chamber section which could be damaged by pressure differences in excess of about 100 μbar.

2.4 Drift chamber electronics, readout, and front end data processing

2.4.1 Introduction

All drift chambers in H1 are connected to one of the three independent branches of the central data acquisition system (CDAQ). The analog signals are digitized and processed in a number of