2 Tracking

The tracking system of H1 provides simultaneous track triggering, reconstruction and particle identification for the event topology particular to HERA electron proton collisions. It has been designed to reconstruct jets with high particle densities and to measure the momentum and angles of charged particles to a precision of $\sigma_p/p^2 \approx 3 \times 10^{-3}$ GeV^{-1} and $\sigma_\theta \approx 1$ mrad.

Because of the asymmetry between the electron and proton beam energies many charged particles are produced at small angles θ to the incident proton (forward) direction. To maintain good efficiency for triggering and reconstruction over the whole solid angle, we divide the tracking system between the central and forward regions (see Figure 2). Two mechanically distinct tracking detectors have been constructed, the central (CTD) and forward (FTD) tracking devices respectively. Each is optimised for tracking and triggering in its angular region.

Track reconstruction in the central region (see Figure 3) is based on two large concentric drift chambers, CJC1 and CJC2. The chambers have wires strung parallel to the beam axes (z-direction) with the drift cells inclined with respect to the radial direction. We have measured a space point resolution of 170 μm in the drift coordinate ($r\phi$ plane) and can, by comparing signals read out at both wire ends, achieve a resolution of one percent of the wire length in z. From the signals recorded in these chambers the transverse track momentum is determined and in addition the specific energy loss dE/dx is used to improve particle identification.

Two thin drift chambers, the central inner (CIZ) and central outer (COZ) z-chambers measure the z coordinates with better accuracy than charge division and complement the measurement of charged track momenta in the central chambers. The CIZ chamber fits inside CJC1, and the COZ chamber fits in between CJC1 and CJC2. These two chambers deliver track elements with typically 300 μm resolution in z and 1 to 2% of 2π in ϕ. This requires a drift direction parallel to, and sense wires perpendicular to the beam axis.

Triggering over the full solid angle is based on multiwire proportional chambers with pad readout in the central and forward region and wire readout in the backward direction. They provide a fast first level (L1) trigger decision which can be used to distinguish between successive beam crossings. Furthermore, in the central and forward region, combinations of pads hit in the central inner proportional chamber (CIP), the central outer proportional chamber (COP) and the forward proportional chambers (FWPC) are used to trigger on tracks coming from a nominal interaction vertex. First level track triggers are also derived from the central drift chambers.

Each of the central chambers has an independent gas volume and separate electrostatic shielding. They were built and tested separately, and then assembled and locked to one mechanical unit. The detector walls are thin to reduce photon conversion, and in particular its effect on identification of primary electrons. Neighbouring volumes share a thin (1.5 mm) cylinder of carbon fiber reinforced epoxy with a 50 μm aluminium coating on each side. The complete system of central tracking detectors is housed in a single aluminium cylinder of 4 mm wall thickness. The assembly also provides a precise alignment of the chambers relative to the outside support.

Charged tracks produced at polar angles θ close to the beam axis (forward $\theta < 30°$, backward $\theta > 150°$) no longer traverse the full bending ($r\phi$) plane radius of the solenoid magnetic field. Consequently in the CTD both track pattern recognition and accuracy of track reconstruction deteriorate as the measured track length and the number of precision space points decrease. A way of rectifying this loss is to compensate for the reductions in track length and the number of points in the central region by means of a higher radial density of accurate space points obtained using wires strung in the bending plane closely spaced in z. This is provided by the forward tracking detector which consists of an integrated assembly of three nearly identical supermodules. Each supermodule includes, in increasing z: three different orientations of planar wire drift chambers designed to provide accurate θ measurements, a multiwire proportional chamber (FWPC) for fast triggering, a passive transition radiator and a radial wire drift chamber which provides accurate $r\phi$ (drift coordinate) information, moderate radius measurement by charge division and limited particle identification by measuring the transition radiation produced immediately upstream.

The FTD and CTD are linked together, aligned and surveyed prior to installation into the calorimeter cryostat.

The description of the individual components of the tracking detector below is followed by sections which describe the features common to all drift chambers, namely the readout and pulse shape analysis and the gas systems used for all chambers.

2.1 Central jet chambers: CJC1 and CJC2

2.1.1 Design criteria

The design of CJC1 and CJC2 [3, 4] follows that of the jet chamber used in the JADE experiment at PETRA [5]. The wire pattern characteristic for a jet chamber is a plane of anode sense wires parallel to the beam line with two adjacent cathode planes shaping the drift field. In the CJC's the latter planes are also made of wires.

A jet chamber cell extends azimuthally from the sense wire plane to both adjacent cathode wire planes, and radially over the full radial span of CJC1 or CJC2 each with no further subdivision, as shown in Fig. 3. This minimises the disturbing influence of field shaping wires at the inner and outer radii.

The jet cells are tilted by about 30° such that in the presence of the magnetic field the ionization electrons drift approximately perpendicular to stiff, high momentum tracks originating from the center. This not only gives optimum track resolution, but also leads to additional advantages. The usual drift chamber ambiguity is easily resolved by connecting track segments of different cells. The wrong mirror track segments do not match, as demonstrated in Figure 4. They also do not point to the event vertex and therefore obstruct only small parts of a real track in the opposite half cell. Each stiff track crosses the sense wire plane at least once in CJC1 and in CJC2. From the fine match at the crossing, the passing time of a particle can be determined to an accuracy σ of ~ 0.5 ns. This allows an easy separation of tracks coming from a different bunch crossing. The drifting electrons from stiff tracks arrive at neighbouring sense wires with a time shift of about 100 ns, and therefore produce only negligible disturbance by cross-talk. Every track traverses several regions of uniform driftfield inside the cells. Systematic errors of drift time measurement, which are known to arise in the nonuniform fields near the cathode and sense wire planes, reverse sign at the crossing, and therefore cancel in good approximation.

Adjacent sense wires are separated by two potential wires (see Figures 3 and 4). This reduces both the surface field and the cross-talk by nearly a factor of two as compared to a single potential wire. Most important, it allows to adjust drift field and gas amplification nearly independently. The actual positions of the sense wires are staggered off the nominal sense wire plane by $\pm 150\ \mu$m, such that adjacent wires are pulled by the electric field to definite positions on opposite sides of the plane.

A cell is azimuthally limited by two cathode wire planes, and at the inner and outer radius by the field wires. The cathode wires are set to a voltage proportional to the distance from the sense wire plane in order to create an uniform drift field and hence a constant drift velocity over almost all the cell. The voltages for the cathode wires are supplied by a resistor network (cathode chain) on the adapter cards connected to the cathode wires. The field wires shape the field at the inner and outer end of the cell such that the deviations from a uniform drift field are minimal. The sense wires are connected to a positive voltage and are AC coupled to the amplifiers. The potential wires are set to ground. To prevent ageing of the chambers due to high electric surface fields, the diameters of the potential, cathode and field wires were chosen conservatively large : 127, 180 and 500 μm. This limits the surface field to $\leq$ 2KV/mm. The anodes are 20 μm (25 μm at the cell ends) gold plated tungsten wires with 3 % rhenium, having a resistivity of 300 Ω/m.

The electrostatics of the cells have been studied in detail by computer simulations. Figure 4 shows drift lines and isochrones in CJC1 for a Lorentz angle of 30°. In most of the drift region the electric field is constant to better than 1 %. At the first and the last sense wires the wire geometry produces local distortions of the field which, however, do not exceed 2 %. This introduces only negligible variations of the drift velocity, in particular around the maximum of the drift velocity.

The parameters of the jet chamber are listed in Table 2. All sense wires are read out at both ends and yield via charge division a $z-$measurement.

2.1.2 Mechanics

The volume of each jet chamber is defined by two endwalls perpendicular to the beam line and an inner and outer cylinder concentric to the beamline. The volume has to be gas tight and to support small overpressure with respect to the atmosphere.

The bulk material of the endwalls was chosen to be 10 mm glass fiber reinforced epoxy [6], combining excellent insulation with good mechanical properties. The fact that there are two jet chambers allowed relatively thin endwalls, because the support lengths between inner and outer cylinders are small and thus the bending under the summed wire tension could be kept below 1 mm.

To facilitate installation, insulation and HV testing of all connections, the signal- and HV leads are integrated into the endwall structure by means of multilayer printed circuit (PC) boards. One board (2 mm thick) covers one drift cell. Of its four layers, one provides a nearly complete electric shield of the chamber, while the others make the contacts between the wire feedthroughs and the (signal and HV) connector sockets. A second PC board inside the chamber, 0.8 mm thick, carries strips for shaping the end fields.

Optimum precision of the wire positions is achieved by first gluing 3 mm thick massive brass pins into pre-bored holes in the endwalls, and then drilling precision holes into the brass. The precision of the sense wire positions, ± 15 μm within one cell is determined by small excentric holes in the brass. Details of the wire supports can be found in ref. [3].

The endwalls are kept apart by four cylinders. For the inner and the outer cylinder of CJC1 and the inner cylinder of CJC2 carbon fiber reinforced epoxy (1.5 mm thick) has been chosen because of its excellent mechanical stability (Young's modulus ϵ = 80 kN/mm^2) and very long radiation length (X_0 = 230 mm). The chamber volume forms a Faraday cage in order to be screened against external electromagnetic noise. Since the conductivity of the carbon fibers is not sufficient in all directions, an aluminium coating of the inner and outer surface was mandatory. The thickness of 50 μm of the Al surface liner was a compromise between electromagnetic screening down to low frequencies (skin depth at 20 MHz in Al is $\approx$ 20 μm) and minimum material. The outer cylinder of CJC2 is made of aluminium (4 mm thick) and is the main support vessel for all tracking detectors. It has feet which slide on rails positioned on the inner warm wall of the liquid argon cryostat and which are the mechanical link to the rest of the H1 detector. At both ends the Al cylinder has thicker flanges (Δr = 12 mm), which are machined to 0.1 mm tolerances in order to house the endwalls precisely. At final assembly the stability and shape of the Al cylinder is guaranteed by the insertion of the endwalls.

	unit	CJC1	CJC2	CIZ	COZ
active length Δz	mm	2200		1800	2160
active zone starts at z	mm	-1125		-1080	-1105
total length Δz[1]	mm	2500		2467	2590
mechanical length Δz	mm	2230		2254	2230
inner radius R_i	mm	203	530	173.5	460
outer radius R_o	mm	451	844	200	485
active radial length	mm	224	296	20	24
number of cells (rings)		30	60	15	24
number of sense wires per cell (ring)		24	32	4	4
number of potential wires per cell (ring)		50	66	3	6
number of field wires per cell		10	10		
number of cathode wires per cell		49	65		
sense wire distance	mm	10.16		5.6(7.0)	6.0
maximum drift distance at R_i	mm	22.9	28.5	61.25	45
maximum drift distance at R_o	mm	44.5	43.1		
sense wire tension	N	0.65		0.2	0.9
mean wire length	mm	2200		1120	2970
drift velocity [2]	mm/μs	$\approx$ 50		52	48.5
$\sigma_{r\phi}$	mm	0.170		28	58
σ_z	mm	22		0.26	0.20
double hit resolution	mm	2		4.6	3.5

Table 2: Central jet and $z-$ chamber parameters.
[1 Incl. preamplifiers; [2] for the gas mixtures given in Table 7.

2.1.3 Calibration and performance

The accurate measurement of the track parameters is limited by the intrinsic resolutions, namely $\sigma_{r\phi} \approx 150$ μm for drift time measurements with a gas mixture of Ar-CO_2-CH_4 (89.5 : 9.5 : 1.0), $\sigma_z \approx 1\%$ of the wirelength for the charge division measurements (limited by pulseheight and noise), and $\sigma_{dE/dx} \approx 6\%$. With this gas the drift velocity at nominal HV is 50 mm/μs.

A large variety of constants is involved to determine the coordinates of a hit from the timing (t) and pulse-integral (Q) of a drift chamber signal (see Section 2.4.5 for (Q,t) analysis). We distinguish overall and wire dependent constants.

The overall constants – event timing, average drift velocity and average Lorentz angle – are sufficient to determine the track parameters with moderate accuracy, e.g. $\sigma_{r\phi} \approx 350$ μm. They are determined and continuously monitored by fitting them as additional parameters to long, high momentum tracks (see Section 2.1.4). The use of an average effective wire length and gain gives resolutions of $\sigma_z \approx 5$ cm and $\sigma_{dE/dx} \approx 17\%$.

The wire dependent constants – timing, signal propagation, absolute gain, relative gain and position of both wire ends – have been determined in two steps. The first step consists of the evaluation of data where the 4 odd/even wires of an 8-channel amplifier card on both chamber ends are pulsed separately and simultaneously. This gives the relative timing of the 4-wire groups, the timing difference, and the relative gain at the two wire ends. The start values for the effective wire length are determined, apart from an overall factor. In the second step the residuals of hits for reconstructed and fitted tracks are evaluated to obtain the absolute values of the individual wire constants. This improves the resolution to $\sigma_{r\phi} = 170$ μm, $\sigma_z = 2.2(3.3)$ cm for protons (pions) and $\sigma_{dE/dx} = 10\%$ (see Figures 5 and 6 and Table 2).

The resolution achieved in the $z-$coordinate depends on the deposited ionization (Figure 5). Data from ep collisions were analysed [7]. The dependence of the specific ionization on the particle momentum is show in Figure 6. There are clearly visible bands for pions, proton and deuterons , where the latter two particle species are mainly produced by protons colliding with the residual gas in the beam pipe.

2.1.4 Track reconstruction

2.1.4.1 Track parametrization Tracks of charged particles are characterized by the five helix parameters: the signed curvature ($\kappa = \pm r^{-1}$, positive if the direction ϕ coincides with a counter-clockwise propagation along the circle), the signed closest distance from the $z-$axis in the $(x, y)-$plane d_{ca}, positive if the vector to the point of closest approach and the trajectory direction form a right-handed system), azimuth and polar angle (ϕ and θ), and the $z-$position (z_0) at the point of closest approach. The first three parameters are determined by a circle fit to the data in the xy-projection using the non-iterative algorithm of Karimäki [8]. The circle equation is expressed in polar coordinates (r, φ) as

$$\frac{1}{2}\kappa\left(r^2 + d_{ca}^2\right) + (1 - \kappa d_{ca})\, r \sin(\phi - \varphi) - d_{ca} = 0$$

For a track traversing both rings of the CJC a single parametrization for both rings is usually sufficiently accurate. Due to multiple scattering in the material between the two rings (2 % X_0) for some tracks two separate sets of parameters are determined, which are constrained to join in a point between the two rings under an angle compatible with the mean multiple scattering angle.

The other two parameters are determined by a linear least-squares fit of $z_i = z_0 + S_i^{xy}(dz/dS)$, where S_i^{xy} is the track length for the point z_i in the xy-projection, with $S^{xy} = 0$ at d_{ca}. The slope parameter (dz/dS) determined by the fit is converted to the angle θ by $\theta = \arctan(1/(dz/dS))$.

The track finding is followed by further modules to determine the xy-vertex for a given run, and to perform track fits to the primary and secondary vertices. The track parameters in this stage are κ, ϕ and θ, together with the xyz-coordinates of the vertex and the error matrix.

2.1.4.2 Track finding Two versions are used for the track finding and fitting. A fast version, efficient for tracks originating from the primary vertex with a momentum > 100 MeV/c, is used on the fourth trigger level filter farm (see Section 5.5 of reference [1]) for background rejection and fast classification of events. It is roughly a factor ten faster than the standard version, which is efficient for all kinds of tracks and is used within the normal reconstruction.

The first phase of track finding, the search for short track elements (curvature negligible), is done independently in the angular cells with 24 (CJC1) and 32 (CJC2) radial wires. Within angular sectors track-element finding does not depend on parameters like the Lorentz angle or the drift velocity. However accurate values of these parameters are necessary when hits from more than one angular cell are combined. Track finding is based almost exclusively on drift time data in the xy-plane and includes removal of outliers, which would distort the circle fit. Only in a later stage the measured z-values are used; here it is again necessary to remove outliers before the data are fitted.

For the fast track finding it is sufficient to determine the bunch crossing time t_0 for an event from the threshold in the drift time histogram. The first step involves the search for track elements defined by three hits within angular cells found on three wires with a wire distance of two. The algorithm starts by trying all pairs of hits at wires $n \pm 2$ (n = wire index). Possible values of drift distances $\bar{d}^n$ at the wire n are calculated by $(d_i^{n-2} + d_k^{n+2})/2$ and/or $|d_i^{n-2} - d_k^{n+2}|/2$ (i, k = hit indices) and stored in a list, if the direction of the pair does not deviate too much from the radial direction. Very dense regions with many hits are not analysed. This list is then compared with the measured values d_j^n and for small differences $|d_j^n - \bar{d}^n|$ the indices of the hits at the three wires are stored as a possible track element. From these hit triplets the curvature κ and the angle ϕ_m can already be determined with sufficient accuracy assuming $d_{ca} \equiv 0$. The parameter ϕ_m is the track angle at the mean radius r_m of the CJC1 and the CJC2, respectively. No attempt is made at this stage to resolve the drift sign ambiguity; triplets with a large value of $|\kappa|$ are rejected, otherwise both solutions are kept. A z-value and a value for dE/dx are assigned to the triplets from the median of the three single-hit values and later used to determine the z-slope and -intercept z_0 and the mean dE/dx value of the track.

Tracks from the origin cluster in the plane of the two parameters κ and ϕ_m of the triplets, with a width of typically only one degree for ϕ_m. These clusters are sufficiently separated, that after finding them a first track definition is achieved. The coordinates of triplets within the clusters are then used in a circle fit, now allowing $d_{ca} \neq 0$, and by a z-fit. Track candidates with large $|d_{ca}|$ and $|\kappa|$ values are rejected.

The track candidates are then checked in the order of decreasing number of triplets (decreasing significance) rejecting tracks with several triplets already used before for an accepted track. Drift sign ambiguities are normally resolved at this stage, since most tracks traverse several cells and the correct solution has a much larger number of triplets than the wrong one. The fast track finding is in general efficient enough to allow sensitive recognition of background or classification of physics events.

The standard track finding starts from the results of the fast track finding and first improves the time reference value t_0 for an event by fits to the drift length values of long tracks. For a given track the values of the circle parameters are used to calculate the expected drift length for all possible wires. The difference between the measured and the expected drift length is then calculated for all hits, taking into account the sign of the drift length. To these differences an expression is fitted, which in addition to a parabolic dependence on the track length (to allow for a small inaccuracy in the track parameters) parametrizes the effect of a t_0 difference (which depends on the sign of the drift length) and of a small difference of the drift velocity. This fit yields an accurate value for t_0 and allows in addition to detect changes of the drift velocity. At the same time the method improves the definition of tracks, since often the range of the hits found is extended. Another circle fit is performed to all long tracks traversing more than one cell (drift sign ambiguity resolved). If the χ^2 value of the track fit (after removing single bad hits eventually) is acceptable the complete set of track parameters is stored already at this stage, the hits assigned to the track are flagged and not used in the following steps.

The first phase of standard track finding again searches for track elements defined by three hits, but now on adjacent wires. All possible wires are considered, except for very dense regions. Triples with common hits are connected by pointers and when all hits of an angular cell are analysed, chains of hits are extracted. These chains of hits are then checked by a fit to the drift times for effects like kinks; eventually long chains of hits are split into two shorter chains. For long chains the staggering of wires sometimes allows already to resolve the drift sign ambiguity; otherwise both solutions are kept. Chains accepted at this stage are stored as track elements with parameters from the fit.

Short track elements are merged to larger ones first within the same or neighbouring angular cells, then within one ring and lastly from both CJC1 and CJC2. The merging algorithm starts with a comparison of pairs of track elements with similar helix parameters. If the distance between them is not so large that they could belong to the same track, a χ^2-fit in the xy-plane is performed. The list of all acceptable pairs is sorted in the order of an increasing "distance", assigned to each pair. The distance is constructed from the χ^2-value and other parameters (e.g. the length of the track element). The list of pairs is then checked sequentially, starting with the "close" pairs. Two elements from a pair are combined to a new (longer) track element, if acceptable. If in this sequence one element of a pair has already been used in the construction of a new element, the fit to the modified element(s) is repeated and rejected eventually. By this process longer and more accurate track elements are formed, starting with the simple and clear cases, thus avoiding with high probability a wrong combination of short track elements.

For the final improvement of the track finding efficiency and precision the expected drift length is calculated for all possible wires and for all track elements ordered by their length. Hits at the expected wires which are not already used by another track are collected. The differences between measured and expected drift length are analysed to reject incompatible hits. Tracks found are allowed to contain rather large gaps of several wires, since parts of tracks may be invisible, especially within jets, due to the limited double track resolution. The fits for the track parameters are repeated using all acceptable hits.

Very short track candidates are rejected, unless they start with the first few wires of a ring. The energy loss dE/dx for a given track is determined from the mean of single-hit values $1/\sqrt{k_i} = 1/\sqrt{(dE/dx)_i}$, excluding hits which are close to another track. An analysis based on a likelihood method has improved the dE/dX to below 10 % (see [9]).

2.1.4.3 Vertex determination The $e-p-$interaction vertex region in the xy-plane extends over a few hundred μm with a rather stable mean position for a sequence of runs. The mean vertex coordinates (x_v, y_v) are determined using long high momentum tracks with a small value of d_{ca} from a few hundred events and minimizing the sum of squares of the distance of the tracks to the vertex.

The known (x_v, y_v) position of the run vertex can be used as a constraint to improve the parameters of tracks originating from this vertex, if the effect of multiple scattering in the beam pipe and the CJC wall for low-momentum tracks is taken into account. Since the standard deviation of the curvature value is roughly inversely proportional to the track length squared, the track precision is significantly improved by this vertex fit in the xy-plane. A z-value of the primary interaction vertex in an event is determined from all tracks fitting to the xy-vertex. The polar angle θ for these tracks is changed accordingly .

Within the standard reconstruction program a search is made for neutral particles decaying into a pair of oppositely charged particles with tracks in the CJC; in addition to K^0_S, Λ and $\bar{\Lambda}$ particles also e^+e^--pairs from conversion are found by this module. Candidate pairs are determined using simple geometrical cuts. For each candidate pair a fit is performed applying geometrical (common secondary vertex of the charged particles) and kinematic constraints. Use is made of the known position of the primary vertex. Momentum balance perpendicular to the direction of the neutral particle is used as kinematic constraint, but no masses are assumed. For a very small opening angle of the pair the transverse momenta in the xy-plane are both constrained to zero, to improve the stability of the fit for e^+e^--pairs. Pairs with an acceptable χ^2-probability are stored.

At later stages of the analysis alternative methods for reconstructing secondary vertices are also employed (see references [10, 11] and Figure 33 of reference [1]). Kalman filtering techniques have also been shown to be useful [12].

2.2 Central $z-$ chambers

The central inner and outer $z-$chambers (CIZ, COZ) surround the inner half of the jet chamber and complement the measurement of charged track momenta in the latter chamber. These two chambers deliver track elements with typically 300 μm resolution in z, which can be linked to