2 General description of the H1 detector

In the design of the H1 detector prime attention has been given to the clean identification of electrons and to their energy measurement. To facilitate this we opted for a large coil, which encloses the electromagnetic and the hadronic calorimeters. With this choice the amount of dead material in front of the calorimeter and its total weight are minimised. Choosing a liquid Argon calorimeter we further benefit from the proven stability of this technique, the ease of its calibration, and the fine granularity which allows to separate electrons from pions to a high degree. Lastly the homogeneity of the response and overall hermiticity are helpful for energy flow measurements as well as missing energy detection. The calorimeter is supplemented by high resolution tracking on the inside and an instrumented iron yoke on the outside for muon detection. In these aspects the H1 detector does not differ strongly from the detectors at e^+e^- colliders, or $p\overline{p}$ colliders built in the past. Specific at HERA are however the high resolution required for hadronic calorimetry as well as the imbalance in the energy of the two colliding beams, which requires an asymmetric detector. Different also is the microstructure of the two beams, which leads to short intervals (96 ns) between two subsequent bunch crossings, and also the high background level, as proton induced background arises from beam line vacuum conditions.

The main elements of the detector are shown in Figure 2. This figure shows as well the reference frame adopted in this experiment.

Since the centre of mass for $e-p$ collisions at HERA is boosted along the proton direction with $\gamma_{cm} = 2.86$ the H1 detector is considerably more massive and highly segmented in this direction. This is apparent from Figure 3, which shows a cut along the beam axis. In the following we often refer to electron direction as the backward direction (negative $z-$values relative to the center of the interaction region and $\theta = \pi$), and the proton direction as the forward direction (positive z and $\theta = 0$).

Starting the description outward from the interaction vertex the detector consists of a central and a forward tracking system, each containing different layers of drift chambers and trigger proportional chambers. The liquid argon cryostat surrounds the trackers. It houses the lead absorber plates and readout gaps of the electromagnetic section, which are followed by the steel plates of the hadronic section with their readout gaps. A superconducting cylindrical coil with a diameter of 6 m and a length of 5.75 m provides the analysing field of 1.15 T. The iron return yoke of the magnet is laminated and filled with limited streamer tubes. The small fraction of hadronic energy leaking out of the back of the calorimeter is registered there, and muon tracks are measured. Muon identification further benefits from additional chambers inside and outside of the iron. Stiff muon tracks in the forward direction are analysed in a supplementary toroidal magnet sandwiched between drift chambers. The remaining holes in the liquid argon (LAr) calorimeter are closed with warm calorimeters, a silicon-copper plug at very forward angles, a Lead-scintillator calorimeter backed by a tail catcher (part of the muon system) in the backward direction and lastly an electron tagger at $z = -33$ m from the interaction point not shown in Figure 3. The tagger marks the energy of an electron with very small scattering angle inducing a photoproduction event and, taken in coincidence with a corresponding photon detector at $z = -103$ m upstream from the interaction point, monitors the luminosity by the bremsstrahlung process. Two scintillator walls in backward direction are installed to recognize background produced by the proton beam upstream of the H1 detector. A survey of detector parameters is given in Table 1.

Three of the major components of the detector, the tracking, calorimetry and muon detection systems are not described in this article. Please refer to an article to be published in a forthcoming issue of this journal for a description of these elements (see [9]) or to [10].

Calorimetry		
Main calorimeter: liquid Argon (LAr)	Electromagnetic part	Hadronic part
Granularity	10 to 100 cm^2	50 to 2000 cm^2
Depth (number of channels)	20 to 30 X_0 (30784)	4.7 to 7 λ_{abs} (13568)
Resolution $\sigma(E_{e,h})/E_{e,h}$	$\approx 11\%/\sqrt{E_e} \oplus 1\%$	$\approx 50\%/\sqrt{E_h} \oplus 2\%$
Stability of electronic calibration	$\leq 0.2\%$ over one month	
LAr purity (decrease of signal)	$\leq 0.2\%$ over one year	
Noise per channel	10 to 30 MeV	
Angular coverage – dead channels	$4^\circ < \theta < 154^\circ$	$< 0.3\%$
Backward calorimeter: Pb–scintillator		
Angular coverage – granularity	$151^\circ < \theta < 176^\circ$	16×16 cm^2
Depth – resolution $\sigma(E_e)/E_e$	21.7 X_0 (1 λ_{abs})	$10\%/\sqrt{E_e} \oplus 1.7$ [1]%
Tail catcher: iron–streamer tubes		
Angular coverage	$4^\circ < \theta < 176^\circ$	
Depth – resolution $\sigma(E_h)/E_h$	4.5 λ_{abs}	$100\%/\sqrt{E_h}$
PLUG calorimeter: Cu–Si		
Angular coverage – granularity	$0.7^\circ < \theta < 3.3^\circ$	5×5 cm^2
Depth – resolution $\sigma(E_h)/E_h$	4.25 λ (44.6 X_0)	$\approx 150\%/\sqrt{E_h}$
Electron tagger: Tl(Cl/Br)		
Angular coverage – granularity	$\theta > 179.7^\circ$	2.2×2.2 cm^2
Depth – resolution $\sigma(E_e)/E_e$	21 X_0	$\approx 10\%/\sqrt{E_e} \oplus 1\%$
Tracking		
Coil: radius – field	3 m – $B = 1.15$ T, $\Delta B/B \leq 2\%$	
Central tracking		
Angular – radial coverage	$25^\circ < \theta < 155^\circ$	$150 < r < 850$ mm
Jet chamber: spatial resolution	$\sigma_{r\phi} = 170\,\mu$m	$\sigma_z = 22.0$ mm
z-chambers: spatial resolution	$\sigma_{r\phi} = 25$ and 58 mm	$\sigma_z \approx 350\,\mu$m
Momentum – dE/dx resolution	$\sigma_p/p^2 < 0.01$ [0.003] GeV^{-1}	$\sigma(dE)/dE = 10$ [6]%
Forward/backward tracking		
Angular – radial coverage (f)	$7^\circ < \theta < 25^\circ$	$120 < r < 800$ mm
Spatial resolution (f)	$\sigma_{r\phi} = 170\,\mu$m ($\sigma_r = 29$ mm)	$\sigma_{x,y} = 210\,\mu$m
Angular coverage – resolution (b)	$155^\circ < \theta < 175^\circ$	$\sigma_{x,y} = 1$ mm
Trigger proportional chambers		
Angular coverage – channels	$7^\circ < \theta < 175^\circ$	3936
Muon detection		
Instrumented iron		
Angular coverage – total area	$4^\circ < \theta < 171^\circ$	4000 m^2
Number of channels	wires: 103700, strips: 28700, pads: 4000	
Spatial resolution	$\sigma_{wire} = 3 - 4$ mm	$\sigma_{strip} = 10 - 15$ mm
Angular – momentum resolution barrel	$\sigma_\theta(\sigma_\phi) = 15(10)$ mrad	$[\sigma_p/p \approx 0.35]$
Forward muon toroid		
Angular coverage – resolution	$3^\circ < \theta < 17^\circ$	$[0.25 < \sigma_p/p < 0.32]$
Overall size (x, y, z) – weight	$12 \times 15 \times 10$ m^3	2800 t

Table 1: Summary of H1 detector parameters.
Alternatively, design and test beam figures are given in brackets [ ]. Energies are given in GeV.

2.1 Electron detection

Scattered electrons are observed in the backward electromagnetic calorimeter (BEMC) for $Q^2 \leq$ 100 GeV^2, in the LAr calorimeter for larger values of Q^2, and for photoproduction events ($Q^2 \approx 0$) in an electron tagger which is part of the luminosity measuring device.

The BEMC is a conventional lead-scintillator sandwich calorimeter with photodiode readout, providing an energy resolution sampling term of $10\%/\sqrt{E}$. The diodes are located in the ≈ 1 T magnetic field. The backward proportional chamber (BPC) located just in front of the BEMC provides the angular measurement of the electron together with track and vertex data given by the central tracker. The kinematic peak in the energy spectrum of the scattered electron at a value corresponding to the electron beam energy allows a precise overall calibration.

The LAr calorimeter covers the polar angular range $4° \leq \theta \leq 154°$ in a single cryostat. The electromagnetic calorimeter with lead absorber plates of total depth of 20 to 30 radiation lengths provides an energy resolution $\sigma/\mathrm{E} \approx 12\ \%/\sqrt{E}$. Electron identification is based on fine transverse and longitudinal shower shape measurement and a cross-check of the absolute energy calibration of the calorimeters is provided by comparing the calorimetric energy measurement of electrons to the corresponding momentum measurement in the central tracking chambers.

Further electron pion discrimination is available by a dE/dX measurement in the central jet chamber (CJC) and by using the transition radiation detectors incorporated into the forward tracker.

2.2 Hadron and jet detection

The hadronic calorimeter with stainless steel absorber is located within the same cryostat as the electromagnetic calorimeter and supports the latter. Both calorimeters together provide the energy measurements of hadrons. Their total depth ranges between 5 and 7 absorption lengths, depending on the polar angle θ. Events with energy leaking out of the LAr calorimeter are efficiently tagged by the tail catcher consisting of the analog readout of the pads of the limited streamer tube system in the iron instrumentation to improve the calorimeter energy resolution. Measurements in a test beam show that the expected resolution $\sigma/\mathrm{E} = 50\ \%/\sqrt{E}$ has been achieved, with an energy independent term of 2%. Here too combining the calorimetric information with the momentum information from the central tracking chambers provides a cross-check of the absolute energy calibration. Further intercalibration between calorimeters is possible by checking the balance in transverse momentum between the electrons and the hadrons.

Low energy hadrons may also be identified by the dE/dX of the CJC.

2.3 Muon detection

An important source of prompt muons at HERA is semileptonic decays of charm- and bottom mesons, therefore the muon system was designed to identify muons within jets. In the large coil solution of H1 the calorimeter serves to absorb the hadronic activity. It moreover allows to detect penetrating single ionizing tracks while the high field provides sufficient bending power for a momentum measurement. The necessary spatial resolution, matched to the dispersion due to the multiple scattering in the material in front of the instrumented iron, is reached with a total of sixteen streamer tube layers with a basic cell size of 10×10 mm^2, a triple layer each in front and after the iron, a double layer after four iron sheets of 75 mm thickness, and eight single layers in the remaining gaps in between the ten iron sheets. The multiple layers are equipped with pads and cathode strips for the measurement of the coordinate perpendicular to the wires.

In the barrel part muons with energies below 1.2 GeV do not reach the first layer, while muons with energies below 2.0 GeV stop within the iron. In the forward direction the effective threshold is 2.5 GeV, but here the muon energy is usually large enough for muons to traverse all 16 layers of chambers. An independent track segment is then measured which can be linked to forward tracker segments. The comparison between momentum measurement in the tracker and through the muon system reduces misidentification and also allows to discriminate against muons from π and K-decay.

In the extreme forward direction the central tracker and the chamber system in the flux return iron are not adequate for measuring muon momenta with sufficient accuracy. This is why a toroidal magnet with an average field of 1.6 T was added. The driftchambers are constructed in such a way, that correlated angle and position measurements are possible. This is needed because the hadronic activity from secondary interactions of the target jet is quite high. The spectrometer is useful in the momentum range between 5 and 200 GeV/c. The lower limit is determined by the amount of material traversed, while beyond the upper limit the muon charge can no longer be measured unambiguously.

2.4 HERA beam features

The electron-proton colliding beam facility HERA consists of two independent accelerators storing respectively 820 GeV protons and 27.5 GeV electrons and colliding the two counter-rotating beams head on in four interaction points spaced evenly along its 6.3 km circumference. Electrons are injected at 12 GeV and are guided by a warm magnet system at 0.165 T, while protons are injected at 40 GeV into a ring with superconducting dipole magnets at 4.68 T. The accelerator was designed for 210 circulating bunches with 760 μA protons and 290 μA electrons each [11, 12] and a luminosity of 1.5×10^{31} cm^{-2}s^{-1}. The bunches are separated in time by 96 ns. In the early phases of operation in 1992 and 1993 only 10 and 90 bunches were circulating, respectively. An indication of the HERA performance in 1992, 1993 and 1994 is given in Figure 6. Since July 1994 the electron beam has been replaced by a positron beam which has considerably improved the beam lifetime at high currents.

Between the last two beam focussing quadrupoles 11.3 m of free space is available for the detector. The beams pass the detector at a height of 5.9 m above floor level ($\approx$ 20 m below ground) at an inclination of 5.88 mrad. Presently a 190 mm inner diameter beam pipe is installed, with a wall of 150 μ Al on the inside backed by 2 mm carbon fibre reinforced plastic comprising 1 % radiation length. Details of the beam line are shown in Figure 5. The beam pipe is cooled with nitrogen gas, which also circulates on the outside of the central tracker to avoid buildup of larger amounts of inflammable gases leaking from the chambers. Incorporated into the beam pipe are a capacitively coupled proton position monitor [13], synchrotron radiation shielding masks (see below), getter pump connections and a flexible bellow to absorb temperature dependent variations of the beam pipe. For the future upgrade of the tracking near the beam pipe [14, 15] a smaller beam pipe with an inner diameter of 90 mm (150 μm Al backed by 0.75 mm carbon fibre) will be installed.

While the radial extension of the beams is small, the finite time spread of the bunches and the zero degree crossing leads to total length of the interaction zone of $\approx \pm 50$ cm. The zero degree crossing was chosen to reduce $e-p$ beam coupling, which could result in beam blow up. The width of the interaction zone is apparent from Figure 6, which shows the projection of central drift chambers tracks onto the beam axis for a background free sample of photoproduction data. Typical vacuum conditions in the beam pipe during the initial running phase lead to a residual gas pressure of $\approx 1-2 \times 10^{-9}$ hPa primarily consisting of atomic hydrogen and carbon monoxyde. Assuming nitrogen as an average representation of the residual gas and a reaction cross-section for protons at 820 GeV ($\sqrt{s} = 39$ GeV) of ≈ 200 mb [16] one expects one proton nitrogen interaction in 10^4 bunch crossings at design luminosity along the interaction region (1 m) compared to one genuine $e-p$ event every 10^5 bunch crossings. The physics rate is dominated by photoproduction giving a visible event rate of about 200 Hz at design luminosity, the beam gas rate given above corresponds to $\approx$ 1 kHz. Beam gas background is not restricted to the interaction zone proper and can originate from the whole proton path through the detector. Furthermore beam halo protons hitting apertures contribute, too. Monte Carlo simulations and measurements from the first data taking period indicate roughly a factor 50 higher rate for the latter process than for beam gas events from the interaction zone. These contributions are however more easily removed in the different trigger and filter levels.

The actual tuning of the luminosity optics for the two beams relies partly on the H1 luminosity system. It makes use of the $ep \rightarrow ep\gamma$ bremsstrahlung process and hence is sensitive to electron interactions with the residual gas. By filling both electron and proton bunch sequences in such a way that there is always at least one bunch of each type with no partner for a collision (pilot bunches) background subtraction can be made. During the filling phase the trigger scintillators of the time-of-flight wall can be remotely removed from the beam pipe. The integrated rate in these counters provides an efficient means for monitoring the quality of the beam tune. Only when a lower value for this rate has been reached the counters are moved back in, and the high voltage on all drift and proportional chambers is raised. While proton fill lifetimes well exceeding 24 h have been reached, the lifetime of the electron ring fills during the HERA startup phase was limited to about 6 hours; since July 1994 when positrons were used, this lifetime has increased by a factor $\approx$ 2.

2.4.1 Synchrotron radiation shielding

The e^- beam is accompanied by a strong flux of synchrotron radiation photons which are produced in the last bending magnet before the interaction point. Synchrotron radiation from the arcs is absorbed before the H1 detector and need not be considered. At a beam energy of 30 GeV and a stored current of 60 mA we expect a flux of 10^{18} photons per second with an energy above 5 keV into the interaction region. This flux represents a radiated power of 3.6 kW. The critical energy is 42.4 keV. In order to protect the detector elements a system of masks inside the beam pipe is installed.

The synchrotron radiation absorbers were designed such that only photons which have undergone at least two scatters can reach the central detector region. In order to reduce the photon flux the aperture of the collimators should be as small as possible. The width is thus determined by the requirement for sufficient aperture at injection. Masks which are hit by synchrotron radiation are sources of secondary photons. Therefore the albedo of all surfaces has been reduced by coating the tungsten absorbers with 0.5 mm silver and 0.2 mm copper. For 100 keV photons the albedo is reduced from 10% for pure tungsten to 1% with the appropriate coating. The geometry of the absorbers is shown in Figure 7. The collimators C_1, C_2 and C_3 are hit by direct synchrotron light and have to stand a radiated power of about 1 kW each. These collimators are movable and water-cooled. The synchrotron radiation which misses C_3 passes through the detector area and hits an absorber 24 m behind the interaction point. The collimators C_4, and C_5 have a fixed horizontal aperture of +30 mm -25 mm and $\pm$ 50 mm, respectively. They protect the detector elements against secondary photons originating from edge scattering at the collimators $C_1 - C_3$ and backscattered photons from the absorber at 24 m. The collimator C_6 is movable and provides an additional shield against photons from 24 m downstream. The aperture can be set between 65 mm and 25 mm with respect to the beam.

The present arrangement of synchrotron radiation masks cuts down the number of photons which enter the central part of the detector to a level of 10^6 photons per second with an energy above 20 keV. Thus at nominal beam conditions we expect about 10^{-1} spurious synchrotron hits in the central tracking chamber per bunch crossing. Due to the low currents and the reduced electron energy of 27.5 GeV we did not observe synchrotron radiation hits in the tracking chambers, consistent with the estimates.

2.5 Detector upgrade

This paper describes the H1 detector as it was up to the end of 1994. During the HERA winter shutdown of 1994-1995 some major upgrade work was done to the detector. It is not the scope of this paper to describe these upgrades, but the subdetectors involved will be enumerated at the end and appropriate references given.