3 Calorimetry

The H1 detector was designed to provide clear identification and precise measurement of electrons, muons and penetrating neutral particles together with good performance in the measurement of jets with high particle densities. These requirements were best met by a calorimeter inside a large coil to minimise both the amount of dead material in front of the electromagnetic calorimeter and the overall size and weight of the calorimeter [57].

The main reasons for choosing the liquid argon technique were good stability and ease of calibration, fine granularity for e/π separation and energy flow measurements as well as homogeneity of response.

Figure 18a shows the longitudinal view of the calorimeters along the beam axis and Figure 18b shows a transverse view of the LAr calorimeter with the wheel structure that is described below. The LAr calorimeter covers the polar angular range between $\theta = 4°$ and $\theta \approx 154°$. The calorimetric coverage is completed with a small calorimeter in the proton direction (PLUG) with copper absorber and silicon pad readout, covering the region between the beam-pipe and the liquid argon cryostat ($\theta \leq 4°$) and a lead scintillator backward electromagnetic calorimeter (BEMC) located in the electron direction after the tracker and covering angles $151° \leq \theta \leq 176°$. The tail-catcher system (TC) is used to provide a rough calorimetric measurement of hadronic particles leaking out of the LAr calorimeter and is based on the analog readout of the pads of the limited streamer tubes that instrument the iron yoke.

In the next section the LAr calorimeter is described; descriptions of the BEMC, the PLUG and the TC can be found in sections 3.2, 3.3 and 3.4 respectively. Further details on the instrumentation of the iron yoke are given in the section on the muon detector (see Section 6). For a more detailed description of the LAr calorimeter system we refer to [58].

3.1 The liquid argon (LAr) calorimeter

3.1.1 Cryostat and cryogenic system

All walls are made of stainless steel except for the inner ones of the warm and cold vessels around the beam pipe and the tracker which are made of aluminium alloy, to minimise the dead material in front of the electromagnetic calorimeter (EMC). The cold vessel is able to withstand a maximum pressure of 3 bars and to support the weight of the calorimeter modules (450 t) and of the liquid argon load (53 m^3). Cooling down to LAr temperature is achieved by circulation of helium gas cooled through an external heat exchanger which is removed when no longer needed. The LAr load is transferred from a 70 m^3 storage tank located at ground level (about 20 m above the detector) into the cryostat through the bottom of the cold vessel. A regulated flow of liquid N_2 through heat exchangers located within the cold and expansion vessels ensures temperature and pressure regulation (1.35 bar). Control of all processes, including cool-down/warm-up and filling/emptying is done by a system controlled by VME processors. Since operations started in early 1991 the calorimeter has remained at liquid argon temperature and most of the time full of liquid argon except for the few days needed to move the detector in or out of the beam. For more details to this system we refer to [58].

3.1.2 Liquid argon purity

A liquid argon purity monitoring system has been integrated into the LAr cryostat to check the stability of the ratio of energy loss to collected charge to the level of $< 1\%$. The basic sensor is a liquid argon ionization chamber to which an electric field of 625 V/mm is applied, corresponding to the nominal field applied to the calorimeter stacks. Its cathode is coated with a ^{207}Bi source of 10^4 Bq activity. The energy spectrum of the radioactive decays is continuously monitored. The data from 11 such probes distributed around the cryostat show that the signal attenuation due to pollution from the stacks is less than 0.5 % per year.

3.1.3 Stack design and construction

The segmentation along the beam axis is done in eight self supporting "wheels" as shown in Figure 18, each of them segmented in ϕ into eight identical stacks or octants. The two forward wheels are somewhat similar in the principle but mechanically assembled as two half rings. An effort was made to minimise dead regions due to cracks.

Common features for all active cells are pad readout on the ground side and a high resistive coated high voltage plane (except for the CBH stacks) with integrated decoupling capacitance as described below.

The hadronic stacks are made of stainless steel absorber plates with independent readout cells inserted between the plates. They define the rigid structure on to which the corresponding electromagnetic stacks are mounted. The orientation of the absorber plates is such that particles are incident on the calorimeter with angles not smaller than 45°. The structure of each electromagnetic stack consists in a pile of G10(epoxy+glass fiber)-Pb-G10 sandwiches separated by spacers defining the LAr gaps. The basic sampling cell is shown in Figure 19a. It consists of 2.4 mm Pb absorber and 2.35 mm liquid argon as active material with, per gap, one readout plane with pads and one high voltage plane coated with high resistive paint (HRC). The latter is a mixture of carbon and glue with a surface resistance of 1-30 $\mathrm{M}\Omega\,/\,\square$, sieveprinted on a Kapton foil. The high resistivity coating provides the HV protection and serves as a distributed decoupling capacity to keep negative cross-talk small. The hadronic sampling cells, as shown in Figure 19b, consist of a total of 19 mm stainless steel, (16 mm absorber from the welded structure and twice 1.5 mm from the plates of the independent readout cells defining the active liquid argon gap) and of a double gap of 2.4 mm liquid argon. They have, in the middle of the active gap, a G10 board with pads on both sides to collect the charges deposited in the gaps. A Kapton foil coated by a layer of HRC (IF2H, FBH, OF stacks) or with copper (CBH) is glued to the inner side of the stainless steel plates, with the same functions as for the electromagnetic modules. The HV is applied to the HRC (or copper for CBH, in which case neon spark gaps mounted close to the gaps act as active protection). For more details we refer to [57, 58]).

The basic calorimetric material constants are given in Table 1 of reference [59]. The granularity of the read-out cells stems from the requirements of a good separation of electromagnetic and of hadronic showers. Longitudinal segmentation is 3– and 4–fold for the EMC over 20 to 30 radiation lengths (X_0) and 4– to 6–fold for the hadronic calorimeter (HAC) over 5 to 8 interaction lengths (λ). Furthermore the tower sizes are such that the channel capacities are kept below 14 nF so that the electronic noise is at a reasonable level, with the additional constraint from the calorimeter trigger that channels belonging to the same trigger tower should have similar capacities within $\pm$ 5% for good timing adjustment.

The high voltage distribution is done by 1504 independent lines. Each line feeds a group of non consecutive planes in a stack, interleaved with planes linked to another HV line to reduce the probability that a complete tower segment be dead in case of a high voltage problem in one line. The present operating voltage of the calorimeter is 1.5 kV which corresponds to an electric field of 625 V/mm. The very good purity observed allows high charge collection efficiency (about 94% [58, 60]) at this low field value, thus minimizing HV problems. After 3 years of operation less than 3% of the high voltage lines do not reach the full voltage.

3.1.4 Electronic system

A major constraint in the design of the system, is that large energies may be deposited at short time intervals (96 ns at HERA) into detectors with large capacities and long collection times, and the information has to be stored until the arrival of the trigger signal ($\approx 2.5\ \mu$s). The basic layout of the electronic chain is described in more detail elsewhere [57, 58]. The preamplifiers, each with two shapers, a slow one and a fast one, are located just outside of the cryostat and feed on one hand the analog readout system where the signals of the slow shapers are read out via two multiplexers giving an overall multiplexing factor of 128, and on the other hand the trigger read out system where the outputs of the fast shapers are processed (see Section 5.3.2.1 of reference [1]). To extend the dynamic range to 14 bits while using a 12-bit ADC, a double transmission system with two different gains for about 50 % of the channels is used thus increasing the number of channels to be read-out to about 65000 (electronic channels). The signals are sent twice via $\approx$ 30 m twisted pair lines to differential line receivers located in the analog receiving unit (ANRU) which performs analog baseline subtraction [61]. Each ANRU serves 512 calorimeter channels and is connected to an ADC board serving 1024 electronic channels that is controlled and read out by a digital signal processor (DSP) module performing data correction. This read-out system is described below (section 3.1.6). The total amount of channels where no signal reaches the preamplifier because of bad contacts within the cryostat is 0.15 % and has remained stable for about three years after closing the cryostat.

3.1.5 Electronic calibration system

To ensure that the calibration of the electronic chain is known and stable to within a few 10^{-3}, calibration capacitors of 47 pF, selected to be within ± 1 %, are used. They are charged with voltage pulses of precisely ($\approx 10^{-3}$) known amplitude.

Two systems have been built into the calorimeter: the first one (cold calibration) with the calibration capacitors in the liquid argon, as close as possible ($\approx$ 1 m) to the gaps, pulses individual channels (one out of 16) allowing detailed cross talk studies. The second system, with calibration capacitors at the preamplifier level (warm calibration), is used mainly as a backup for calibrating channels with a problem in the calibration line within the cryostat. In this case an extrapolation technique developed during the runs in test beams at CERN is used, and a precision of the order of 1 % in the determination of the calibration constants is achieved. This method is presently applied to less than 1 % of the 45000 calorimeter channels.

A third order fit to the calibration data is performed for each channel [58] from which the constants to be downloaded into the DSPs are determined. At H1 such operations are done once every few weeks. Figure 20 shows the stability of the calibration constants over one month.

The calibration constants need no correction for diagonal cross-talk as they are determined by pulsing the cells individually using the high granularity cold calibration system. Non diagonal cross-talk has been determined from the test beam data and was found to be small ($\leq 0.5\%$), mainly affecting the CBH modules.

3.1.6 Calorimeter data acquisition

The calorimeter data acquisition system reads out data from the LAr calorimeter, the BEMC, the PLUG calorimeter and the analog part of the instrumented iron (TC). These detectors have the same readout electronics starting from the ANRU. The LAr calorimeter yields most of the data and its readout is described here. At the preamplifier level the data are split into two paths as mentioned in section 3.1.4. In the analog data path the first level trigger decision samples the slow shaper pulse at its maximum. At the level 2 trigger (L2), 20 μs after the collision, the analog to digital conversion of the 65000 electronic channels is started (total encoding time is 1.2 ms). The ADC counts of all electronic channels are then converted into calibrated charges by 69 DSPs working in parallel. The DSP boards [62] used here are based on the Motorola DSP56001 and perform for each cell a noise suppression done in parallel to the encoding and an order three polynomial correction. These DSPs provide calibrated charges formatted with the offline numbering of the calorimeter cells. On-board memories are downloaded with the current set of calibration constants (for each channel four parameters and the 1σ noise value are needed). The code contains less than 200 instructions. It is written in assembler language and was optimised to fit into timing specifications and the available program memory space in the DSP chip.

In the trigger data path, the pipelined trigger chain produces digital sums for each of the 22 bunch crossings following the collision. A first level trigger decision (L1) based on total and transversal energies is derived within 2.5 μs. Ten dedicated DSPs read the data of the fast shapers (see Section 5.3.2.1 of reference [1]). They verify the timing and the shape integrity of the trigger tower signals, calculate pileup estimators based on charge and time analysis, and report any malfunctionings [63]. They store the signal history of a total of 474 trigger towers over 256 bunch crossings around the trigger time (t_0). From these data, every second sample in the interval ranging from -25 to +25 bunch crossings is read out for pileup studies. The DSP boards used in this path are based on the same DSP chip as for the analog data read out but are of a different design, with a special interface to the trigger data.

The formatted data for both paths, within independent VME branches, are collected by two event builders based on the RISC processor AM29000 running the real time kernel VRTX. The AM29000 event builders, one for the analog data and the other for the trigger data, run on top of the real time kernel VRTX, with minimal system overhead. The data are passed to the event logging task through a circular buffer. The event is then formatted and sent to the central data acquisition through an optical fiber link (see Section 7.1.2 of reference [1]).

Presently with an event size for the calorimeter branch of about 20 Kbyte and a first order dead time of 1.2ms the maximum data taking rate has been measured to be 200 Hz (100 % dead time). At a rate of 100 Hz the dead-time is 15 %.

A processor based on the Motorola 68030 chip and operating under an OS9 system is used for run control and as a stand alone facility.

3.1.7 Reconstruction techniques

Input to LAr calorimeter reconstruction are calibrated charges for each calorimeter cell, as provided by the DSPs. The calorimeter reconstruction program converts charges to energies in the calorimeter cells for both hadronic and electromagnetic showers, corrected for the effects of dead material, eliminates electronic noise and forms clusters from groups of cells.

The scaling from charge to energy (electromagnetic scale (see Section 3.1.8)) involves a charge to energy calibration factor (determined for each stack geometry in calibration runs at CERN, see Section 3.1.8), a correction for the charge collection efficiency for operating at 1500 V (derived from HV curves obtained with cosmic muons [58]) and correction factors for local variations of gap and absorber thicknesses (measured during stack construction).

The noise is measured for each channel during electronic calibration. It varies between 15 and 30 MeV equivalent energy depending on the calorimeter region (see Table 8). In events recorded with a random trigger 1100 cells out of a total of 45000 cells pass a $+2\sigma$ noise threshold on

	CB	IF
EMC	30 MeV/0.25 mips	15 MeV/.15 mips
HAC	30 MeV/0.15 mips	24 MeV/.15 mips

Table 8: Approximate energies and minimum ionizing particle equivalents (mips) corresponding to 1σ noise in the electromagnetic and hadronic sections of the central barrel and inner forward modules respectively.

average. Adding up this energy for the full calorimeter yields an average value of 48 GeV with a standard deviation of 3 GeV (Figure 21a). To suppress the noise further we use the negative noise, present in the gaussian distributed noise signals after pedestal subtraction, to compensate the positive noise contribution to the measured signal. We keep cells above $+4\sigma$ (signal seed) and all neighbours in a $3 \times 3 \times 3$ cube around a seed cell ($> +4\sigma$) also to keep small signals at the fringe of showers. In order to compensate for noise picked up in the previous step also cells below -2σ around a signal seed are kept. Cells below -4σ are kept in order to compensate for noise contribution to $+4\sigma$ seed cells. No neighbours are collected around these -4σ cells which are purely noise. After this procedure, the residual noise contribution is 0.1 GeV with a $\sigma = 0.5$ GeV (Figure 21b).

The signal loss introduced by the above noise suppression procedure has been studied with simulated low Q^2 DIS events. In these events the hadronic energies are low, with average deposited energies in the barrel region of the calorimeter of about 4.5 GeV, 800 MeV for hadrons and 400 MeV for photons. In this (most difficult) case 17 % of the energy is lost due to this noise suppression. For high Q^2 events ($< Q^2 > \approx 500$ GeV^2) the loss is smaller (5 %). These losses are corrected for in the reconstruction of hadronic energy (see Section 3.1.7.5).

For simulations, noise is included for each cell by using events recorded with random triggers in special runs with no online noise suppression.

3.1.7.1 Clustering All cells passing the cell level reconstruction are subject to clustering. The algorithms used are tuned so that the cells containing energy depositions from an electromagnetic shower initiated by a photon or electron are most probably merged into one cluster. Hadronic showers on the other hand, with their large spatial fluctuations are in general split into several clusters.

3.1.7.2 Further noise suppression Clustering allows further reduction of the noise in the hadronic part of the calorimeter. A hadron penetrating deeply inside the calorimeter usually deposits enough energy to form at least one cluster with a signal well above the noise level. Other small isolated energy depositions which are not distinguishable from noise are correlated in space with this prominent cluster.

Small signals are suppressed if they are in the last layer of EMC or in HAC and far away (> 50 cm) from the direction given by the centre of gravity of any prominent cluster (significance, $\sqrt{\sum(E_i/\sigma_{noise})^2}$ above 8) and the nominal interaction point.

This suppression does not increase the signal loss mentioned in Section 3.1.7. The energy distribution of noise remaining in empty events after the suppression peaks at zero with a sigma of 0.25 GeV, as can be seen in Figure 21b.

3.1.7.3 Correction for energy loss in dead material The energy losses in dead material in front of the calorimeter (the beam pipe, the central tracker and the inner cryostat wall) and in cracks between the calorimeter stacks are quite substantial. In low Q^2 DIS events they amount to $\approx$ 10 % of the energy deposited in the calorimeter, dead materials in front of the calorimeter accounting for about 90% of these.

Corrections for the energy loss were derived using Monte Carlo simulations. The event by event corrections are based on the measured calorimetric energies. To reduce the influence of noise on the correction, only cells with energy above $3\sigma_{noise}$ for cells in prominent clusters (see Section 3.1.7.1) and above $5\sigma_{noise}$, otherwise, are considered.

Energy losses in front of the LAr calorimeter are corrected by using the first (inner) layer of cells in the LAr calorimeter. For each cell in the first layer with a signal above the threshold mentioned above, an energy is added according to:

$$E^i_{loss} = \alpha_{fr} f^i_{dead}$$

Here f^i_{dead} is the energy loss of a minimum ionizing particle in the material in front of cell i in projective geometry with respect to the nominal interaction point. A global factor α_{fr} was determined for each half wheel along the beam direction by simulation. For the above energy estimate we use only the fact of the presence of an energetic cell, but not its energy. This approach allows a common correction procedure for losses caused by electrons and hadrons.

The correlation between the estimate of the energy losses in the reconstruction and the true energy lost in front of the calorimeter for simulated low Q^2 DIS events is given in Figure 22. An example of the effect of the dead material correction for experimental data is shown in Figure 23, where the π^0 peak in the effective mass of two photons (e.m. clusters) is moved by the correction into the region of the π^0 mass.

The correction procedure for energy losses in a crack uses cells in the layers nearest to the crack and on either side of it. Cells on one side of a crack are coupled with cells on the other side and for each such pair an energy loss between them is estimated by

$$E^j_{loss} = \beta f^j_{dead} E^j_l E^j_r / (E^j_l + E^j_r)$$

distributed between the two cells of a pair in proportion to the cell energy. Here E^j_l and E^j_r are energies in a pair j deposited at left and right sides of the crack. The function f^j_{dead} takes into account local inhomogeneities of dead materials. A global factor β was determined for each type of a crack. These factors differ considerably for pions and electrons. For the moment, only corrections of hadronic type are used in the reconstruction because of difficulties in the separation of hadronic and electromagnetic components in ϕ and z crack regions.

Figure 24 shows the performance of the dead material correction as function of θ and ϕ for simulated pions of 20 GeV. The crack structure which is clearly seen before the correction nearly vanishes after the correction. The CB2/CB3 z-crack almost pointing to the interaction point was scanned by a pion test beam of 30 GeV at CERN. Results are given in Figure 25. The response across the crack is well described in simulation.

3.1.7.4 The hadronic energy scale The LAr calorimeter is non compensating. The charge output for hadrons is about 30 % smaller than for electrons. Therefore an additional correction has to be applied to the signal obtained on the electromagnetic scale.

The fine segmentation of the LAr calorimeter allows to distinguish the primary electromagnetic component of a jet which is already on the correct (electromagnetic) energy scale. It also allows a high level of compensation within hadronic showers to be reached by weighting signals from individual calorimeter cells (see below).

The primary electromagnetic clusters are filtered using such characteristics as the fraction of cluster energy deposited in EMC (containment in EMC), in the first layer of EMC (early shower development), and in the four most energetic cells of a cluster (compactness); see reference [59]. The filtering is done for clusters with an energy above 1 GeV.

The hadronic objects in the reconstruction are formed by cells which are not included in an electromagnetic cluster and are located within a radius r around the direction given by the nominal interaction point and the centre of gravity of the hadronic cluster ($r < 25$ cm in EMC and $r < 50$ cm in HAC). Here, a cluster is called hadronic if it is prominent (see Section 3.1.7.3) and if it is not recognized in the filtering as an electromagnetic one or, at lower energies, if it is developing deeply inside the calorimeter.

To get the proper hadronic scale for hadrons, a software weighting technique is applied, which was initially proposed by the CCFR Collaboration and used in the CDHS experiment [64]. This method was further developed by H1 on the basis of CERN test runs [65, 66, 67, 68, 69]. The aim is to equalize the response to the electromagnetic and hadronic components of a hadronic shower and, therefore, to suppress the influence of the large fluctuations in the hadronic shower composition on the reconstructed energy. The technique exploits the fact that local energy deposits of high density are mainly of electromagnetic origin while the hadronic component is much more spread out. Thus, in a well segmented calorimeter the amount of energy deposited in the cells can be used for statistical separation of electromagnetic and hadronic energy depositions.

In the reconstruction the weighted energy in a cell i, E^i_{rec}, is calculated from the cell energy on the electromagnetic energy scale, E^i_0, by:

$$E^i_{rec} = \{a_0 + a_1 exp(-\alpha E^i_0/V^i)\}E^i_0$$

where, a_0, a_1, and α are the parameters of the weighting function (different for EMC and for HAC) and V^i is the volume of the cell. These parameters were determined as function of the reconstructed jet energy (calculated inside cones of 10°) using a Monte Carlo simulation of jets [70]. For hadrons with energy below 7 GeV this ansatz is replaced by simple multiplicative factors corresponding to effective e/π ratios in EMC and HAC. In the region 7 to 10 GeV both methods contribute to the correction in order to get a smooth transition from the simple correction factors to the weighting.

The remaining cells not included into electromagnetic clusters or hadronic objects are due to low energy particles depositing energy in the first two (three in the forward region) inner layers of the calorimeter. These leftovers are affected by noise, and the energy correction to be applied depends on particle composition and energy spectra. The corresponding correction factors were defined using simulated low Q^2 DIS events.

3.1.8 Calibration and performance

The most important task in understanding the calorimeter modules is the energy calibration. This was done by putting full scale calorimeter modules in a test beam at CERN. Checks of the calibration quality were done once the H1 detector was fully operational by using various techniques as described below, such as determining the response of the electromagnetic calorimeter to electrons generated by cosmic muons crossing the detector or verifying the P_t balance between the electromagnetic and the hadronic energy in deep inelastic events at HERA.

3.1.8.1 Overview of the test runs at CERN An extensive calibration program with $e-$, $\pi-$ and $\mu-$ beams was performed in the H6 test beam at the CERN SPS with prototypes [65, 66, 71] and with modules installed later in the H1 cryostat at HERA [72, 73]. These beam tests supplied the basic calibration constants of the calorimeter.

Only one of each type of the calorimeter stacks was tested as the very strict mechanical constraints (see references [57, 58]) needed to reach a homogeneity at the 1 % level were achieved during the construction phase, allowing to transfer calibration constants from one module to another.

Eight characteristic stack configurations were tested separately using the same beam setup, calorimeter readout and calibration electronics. These configurations include a full coverage of θ and all important crack configurations [72, 73]. Special modules consisting of half stacks assembled to reproduce a CB2-CB3 ϕ crack (see reference [74] and an FB1-FB2 ϕ crack (see references [75, 76]) were built and put into the test beam in 1992.

The purity of the liquid argon was constantly monitored by probes identical to those used in the detector described in section 3.1.2. The decrease of the signal with time was much faster than in the H1 detector because of polluting agents brought by the stacks. It was not possible to use the same flushing and cool-down procedures for the test set-up as in the final detector. Big variations in the pollution rate from one configuration to the next were attributed to the different cleaning agents used during the construction of the stacks which were built at various institutes.

The same front end electronics scheme and calibration system as at HERA was used as much as possible. Data were taken with beam energies in the range 3.7 to 80 GeV for electrons and 3.7 to 205 GeV for pions.

In some of the data taking periods a tail catcher module was added behind the hadronic calorimeter allowing combined analyses [66, 72]. The tail catcher modules were also calibrated in standalone tests [77].

3.1.8.2 Test beam results For the electromagnetic energy scale two calibration constants (c_{EMC}^{exp}, c_{HAC}^{exp}) were determined for each wheel, which transform the measured electric charge Q_i per cell into energy deposited by electron showers. Corresponding constants (c_{EMC}^{MC}, c_{HAC}^{MC}), transforming visible energy into deposited energy are obtained in Monte Carlo simulations (MC) for electrons (of 30 GeV). These constants are defined to be independent of effects of dead materials in front of the calorimeter, any leakage and analysis cuts.

The corresponding experimental constant c_{EMC}^{exp} is obtained by a comparison (see Figure 26) of experimental data with detailed simulation of the test setup and requiring the reconstructed energies to agree:

$$E_{rec}^{exp} = c_{EMC}^{exp} \sum_{i}^{EMC} Q_i = E_{rec}^{MC} = c_{EMC}^{MC} \sum_{j}^{EMC} E_j^{vis} \tag{1}$$

For the calibration constant a value of $c_{EMC}^{exp} = 3.55$ GeV/pC is obtained on average. For the hadronic stacks no electron data were available and $c_{HAC}^{exp} = 7.1$ GeV/pC was obtained by scaling the value of the EMC by MC.

The resolutions σ/E obtained for various stacks are in the range 10 % to 13 %/$\sqrt{E}$ with constant terms below 1 %. Figure 27 shows the results for four different stacks and the parametrization for FB2 according

$$\sigma/E = \sqrt{A^2/E + B^2/E^2 + C^2} \tag{2}$$

with $A = 11\%\sqrt{E}$, $B = 154$ MeV and $C = 0.6\%$. The measured resolutions differ at low energies due to different handling and influence of electronic noise for the various stacks. The observed non linearities are below 1 % after corrections for effects of dead material and noise by Monte Carlo.

The calibration constants of the various stacks were found to vary by about 2.5 % . This is larger than expected from the known mechanical differences of different wheels. The main error source were impurities in the liquid argon during the CERN test. The variation is consistent with the systematic error of the extrapolations of the high voltage plateau curves by which the charge collection efficiency was determined. Further tests of the energy scale are possible at HERA (see below). For further results on the calibration by test beam electrons and simulations we refer to [73] and for more details to [69, 78, 79, 80, 81, 82, 83].

The response to pions has been extensively studied for the different calorimeter wheels and compared to detailed simulations (compare references [72, 69, 84, 81, 85, 86, 87]). An application of the standard H1 reconstruction code (section 3.1.7) is shown in Figure 28, where data and GHEISHA simulation [88, 89] for pions at 80 GeV are compared in 3 different wheels on the electromagnetic scale and after reconstruction of hadronic energies. No attempt is made here to correct for leakage. The effect of the inclusion of the streamer tube tail catcher (see Section 3.4 and reference [90]) which adds at the test beam another 4.5 interaction lengths (λ_{abs}) to the 6 of the IF wheel, can be seen in Figure 29. It shows the reconstruction at a pion energy of 205 GeV for all events and for those fully contained in liquid argon. The obtained resolutions are about $\sigma/\mathrm{E} = 50\ \%/\sqrt{E}$ with an energy independent term of 2 % as shown in Figure 30.

3.1.8.3 Performance at HERA Data taken at HERA, since April 1991 with cosmic muons, and since June 1992 with beams, allowed for checks of both the overall electromagnetic and hadronic energy scales.

The orientation of the three CB wheels is especially favourable for the study of the signals from cosmic muons and allowed to check the charge collection, the overall calibration and the time stability. The charge collection efficiency at the operating voltage of 1.5kV was determined by high voltage plateau curves to be $.944 \pm .014$. The electromagnetic energy scale as determined at the CERN beam tests (see above) could be verified to $\pm$ 8 % ([60]). More precise tests are possible with electrons (see below).

The overall response to muons of the individual electromagnetic and hadronic sections of the three CB wheels varied from October 91 to November 94 by less than $\pm$ 3 %.

A fraction of the cosmic muons traversing the detector generates electrons. Their momentum p can be measured in the central tracker CJC and can be compared with the energy E measured mainly in the CB wheels. A typical event is shown in Figure 31 together with the measured E/p distribution for selected electrons with $p > 1$ GeV/c and incident angles below 25° with respect to the normal of the calorimeter plates. The mean (0.96 ± 0.01) and width $(\sigma = 0.15)$ agree with the simulation within errors. The width corresponds to a resolution of $\sigma/E = 0.20/\sqrt{E}$, but this value is still influenced at these energies ($<p> = 1.6$ GeV/c) by noise and dead material corrections (section 3.1.7) of about 10 %.

With these techniques the forward wheels cannot be reached, but the performance of IF and FB wheels can be checked by two photon mass spectra as demonstrated in Figure 23 which shows a clear π^0 mass peak.

Deep inelastic scattering events where the scattered electron and the hadronic jet are detected both in the LAr calorimeter can be used for a direct comparison of the hadronic and electromagnetic energy measurement exploiting p_t balance. The transverse components p_{te} and p_{th} are calculated by summing vectorially the calorimeter cell energies. Figure 32 shows that the measured energy balance is compatible with simulation.

3.2 The backward electromagnetic calorimeter (BEMC)

The backward ($-z$) region of the H1 detector is instrumented with a conventional electromagnetic lead-scintillator sandwich calorimeter.

The primary task of this backward electromagnetic calorimeter is to measure energies and directions of electrons scattered under small angles from DIS processes. In addition the BEMC contributes to the measurement of hadrons emerging from photoproduction and medium to low-x, high-y hadronic final states from DIS.

The kinematics of DIS accessible with this calorimeter is characterised by moderate four-momentum transfers 5 GeV^2 $< Q^2 <$ 100 GeV^2. Such processes dominate by far the DIS cross section-observed in the H1 detector and provide the only access to the low-x part of the proton structure ($x \approx 10^{-4}$). At the same time the calorimeter has to operate in a very high rate environment caused by the illumination of the rear side with secondary hadrons originating from beam-gas and beam-wall interactions of the 820 GeV proton beam. Due to its location within the large solenoid the BEMC is exposed to the full magnetic field of 1.15 T.

A full description of the BEMC and its associated trigger, the backward single electron trigger (BSET) can be found in [91].

3.2.1 Mechanical layout

The calorimeter elements (stacks) of the BEMC are mounted in an aluminium barrel with a diameter of 162 cm. The front face is located at a distance of 144 cm from the nominal interaction point. Scattering angles θ from 151° to 176° are covered with full azimuthal acceptance. This corresponds to $\approx$ 1.4 units of pseudorapidity η ranging from -2.9 to -1.6

Granularity of the calorimeter is provided by segmentation into 88 calorimeter stacks aligned parallel to the beam line. The transverse structure can be seen in Figure 33a. 56 stacks have a square cross-section. The remaining ones are of trapezoidal and triangular shapes in order to provide an approximation to the circular shape of the support barrel.

The stacks are multilayer lead-scintillator sandwich structures with 50 active sampling layers made of SCSN-38 plastic scintillator [92] of 4 mm thickness. The entire structure (figures 33b,c) corresponds to a total of 21.7 radiation lengths or $\approx 1\ \lambda$. The Moliere radius is 3.4 cm. The scintillation light is coupled via a 0.3 mm air gap to Y-7 wavelength shifter bars [92]. Two pairs of 8 cm wide bars cover two opposite sides of a square stack extending over the full active length. The remaining two sides are covered with 16 cm wide bars extending only over the last 15 sampling layers in the stack, thus providing a twofold segmentation in depth.

The light emitted in the wavelength shifter bars is detected by PIN photodiodes (S2575 [93]). Each long bar is equipped with one diode. The short bars are connected to a pair of diodes due to their double width. Special arrangements of wavelength shifters have been made for the non-square stacks. Some of them have a reduced number of readout channels. In total there are 472 read-out channels in the BEMC.

3.2.2 Readout electronics and trigger

The electronics associated with the BEMC must fulfill two main functions. It processes the analog signals from the PIN photodiodes and converts them into digital form with the required speed, precision and stability. It further provides trigger signals.

The signals from the PIN photodiodes are fed into charge sensitive pre-amplifiers mounted directly on the back of each calorimeter stack. The preamplifiers produce fast signals of 100 ns rise time and a fall time of 150 μs. A differential pulse is sent from a line driver through 30 m twisted pair cables to a receiver located in an electronics hut. Here the signals are split to provide input for the calorimetric triggers and for the readout.

Two trigger signals are produced. Firstly the analog signals of the four long wavelength shifter bars within one stack are summed in order to provide input for the high granularity backward single electron trigger (BSET; see Section 5.3.2.2 in reference [1]). A second set of stack sums is being formed to feed the overall calorimeter trigger sums with low granularity. The timing and the gain of the BSET stack sums are individually adjusted in order to assign events uniquely to one bunch crossing and to compensate for stack-to-stack variations in energy calibration already on the first trigger level.

The readout of BEMC energies proceeds through a chain of shapers, sample-and-hold circuits and multiplexing similar to the one of the LAr calorimeter described previously. Due to the large cross-section of calorimeter stacks and the high proton beam related background rates the concept of slow shaping to match the trigger level L1 decision after 25 bunch crossings cannot be applied for the BEMC. The probability for a distortion of the energy measurement through pile-up would exceed 50 % for a background rate of 100 kHz. To overcome this problem an analog electronics chain consisting of a fast, unipolar shaper and a subsequent analog delay line is used. The shaper has a time constant of 450 ns (FWHM) in order to reduce the pile-up window to about five bunch crossings. To match the trigger decision time the shaped signal is delayed by an analog delay line with a length of 2.4 μs [94]. The fast shaping requires a precise relative adjustment of all 472 delay lines in order to avoid channel-to-channel gain variations of the signal. Equalization of the delay lines to 60 ns is required to keep the gain variations within 1 %. The equalization achieved is better than 10 ns so that there is no contribution to the energy scale uncertainty from this source.

3.2.3 Calibration

The calibration of the BEMC is based on two contributions. Electronics gain and light collection in the stacks are factorised and monitored independently.

The gain of the electronics chain is determined with a pulser system identical to the one used for the LAr calorimeter. The pulser system measures the response of the entire electronics chain including all cables. It has also been used to transfer the initial absolute calibration from test beams to the final experiment. During data taking periods the entire electronics is calibrated once per week. The stability achieved is better than 0.1 %. This is far below other sources of calibration uncertainties.

The second contribution to BEMC calibration is light collection and detection in the calorimeter stacks. Here the concept is to obtain the initial absolute energy scale from testbeam measurements and to confirm and improve the scale in situ using electrons scattered under small angles from medium/high x_{Bj} partons, i.e. in the kinematic peak.

The initial absolute calibration of individual square stacks has been obtained from measurements with a 5 GeV electron beam at the DESY synchrotron. The individual calibration constants of channels in quadratic stacks differ only slightly with a spread of 6 %. This demonstrates the stable and well reproducible construction procedure for the optical part of the calorimeter.

In the environment of HERA $e-p$ collisions the BEMC is exposed to a cross-section of 100 nb from DIS. Deep inelastic scattering at small angles from medium/high x_{Bj} partons gives rise to a peak in the distribution of scattered electron energies at the value of the electron beam energy.

A method has been devised to use this peak for a precise determination of the calorimeter energy scale for electrons. The method has been successfully applied to the high statistics data sample collected in the 1993 and 1994 running periods [95]. The calibrated energy distribution observed in the BEMC is shown in Figure 34. The data points are compared to a simulation program taking into account energy losses in dead material as well as spatial inhomogeneities and all known contributions to the energy resolution.

3.2.4 Performance

The overall electromagnetic energy scale of the BEMC has been determined using the data taken in the 1994 run period. In figure 34 a comparison of the measured energy distribution of the leading cluster with a simulated one (shaded area) using the GRV structure function is shown after adjustment of the calibration for each individual stack using the kinematic peak method. Good matching of the data and the simulation proves the quality of the BEMC calibration and of the understanding of the detector response. In the 1994 luminosity period the global energy scale for electrons in DIS was adjusted using the kinematic peak method with a precision corresponding to 1 % dominated by systematical errors.

The energy resolution of the BEMC has initially been determined in test beam studies carried out with electron beams ranging from 1 GeV to 60 GeV. A sampling term of $10\%/\sqrt{E}$ has been found in agreement with expectations from the mechanical design. The average noise per calorimeter stack was measured to be 130 MeV in the real H1 environment. Energy clustering is carried out over stack nonets giving rise to a contribution of 390 MeV from noise for each cluster. The constant term in energy resolution for a single stack was found to be 1.7 %. Using the observed shape of the kinematic peak the residual stack-to-stack calibration uncertainty has been determined to be 0.3% for electrons depositing more than 95% of their energy in a single stack.

The inherent mechanical non-uniformities in the stack construction due to the wavelength shifters cause an impact point dependent response to electromagnetic showers. Extensive studies carried out with test beam data and shower simulations exhibit a regular pattern of inhomogeneities with losses up to 8 % close to the wavelength shifters. A look-up table has been created to correct this impact point dependence. Electrons sharing their energy among many stacks receive an additional contribution of 3 % to their effective resolution caused by imperfections in the correction procedure.

The matching of electron tracks measured in the tracking detectors to the cluster position reconstructed in the BEMC has been determined from DIS events with the electron scattered into the BEMC. Based on the known attenuation properties of light in the scintillator plates a position resolution of 7 mm transverse to the beam has been achieved.

Interacting hadrons deposit typically 45 % of their energy in the BEMC. A satisfactory hadronic resolution of $\approx 80\%/\sqrt{E}$ has been estimated in detector simulations by combining the measurements in the BEMC and in the instrumented iron structure behind it with proper weighting.

3.3 The plug calorimeter.

The plug calorimeter (PLUG) has been designed to close the gap of acceptance for the energy flow measurements between the beam pipe ($\theta \approx 0.6$ °) and the forward part of the LAr calorimeter ($\theta \approx 3.5$ °). Its main task is to minimise the missing part of the total transverse momentum due to hadrons emitted close to the beam pipe. In addition the energy, emitted into a narrow cone

Position	$+476 \leq z \leq +545$ cm
Overall radius	$6 \leq r \leq 32$ cm
Radius of detector planes	$6 \leq r \leq 25$ cm
Polar angular range	$12.5 \leq \theta \leq 58$ mrad
Number of detectors	$8 \times 84 = 672$
Number of electronic channels	$4 \times 84 = 336$
Total length	69 cm $\equiv 4.25\lambda_{abs} \equiv 44.6X_0$
Weight	1.48 t

Table 9: Global parameters of the PLUG calorimeter

around the beam pipe can be used to separate the proton jet as well as to veto beam gas and beam wall background.

Owing to the geometrical constraints – the available space inside the return yoke of the H1 magnet was restricted to a cylindrical hole of ≈ 0.7 m length and a diameter of ≈ 0.7 m around the beam axis – only a most compact calorimeter could fit. Facing the physical requirements of good angular resolution, nearly full containment and linearity, the solution was a sampling calorimeter consisting of nine copper absorber plates interleaved with eight sensitive layers of large area silicon detectors [57]. The most important construction parameters are given in Table 9.

Figure 35 shows a schematic view of one of the two half-cylindrical parts of the PLUG calorimeter, each mounted in one half of the return yoke. The detector modules are placed within 15 mm wide slots between the absorber plates. These are sealed and easy to replace entities, which contain one half of a detector plane each. Between two 5 mm copper plates a G10 readout board, equipped with 42 silicon detectors of 400 μm thickness, is placed (Figure 35, left part). A detailed description of the detector technology can be found in [96]. Typical characteristics of single silicon detectors, as measured in the laboratory, are given in Figure 36. Due to a special edge-protection procedure 32 quadratic (5×5 cm^2), six triangular and four rectangular detectors cover one half of the detector plane in a mosaic structure nearly completely, leaving only 4% of the total area inactive. A total of 672 detectors have been installed.

The readout electronics of the PLUG are included in the analog chain of the H1 calorimeters and use the same components (see Section 3.1.6). The 672 detectors are read out in 336 pairs of channels. Trigger towers are built by merging the signals from subsequent channels in the $z-$direction.

The calibration of the ADC output in units of visible energy rests on an absolute energy measurement using α-particles. Its conversion into total absorbed energy is based on detailed MC-simulation studies of electromagnetic and hadronic shower developments in silicon instrumented calorimeters in comparison with test measurements [97, 98, 99, 100, 101].

Since March 1994 the PLUG was operated with 8 instrumented detector planes. During luminosity operation sharp increases of detector dark currents up to 15 % were observed which could be correlated with failures of HERA machine components and consequential increase in proton-related backgrounds (see references [102, 103]).

The energy resolution of the PLUG calorimeter suffers from both the amount of dead material in front of the device and the energy leakage. Nevertheless its value of about $150\%/\sqrt{E}$, evaluated from experiment supported MC-calculations [100], turns out to be sufficient for the tasks within the H1 experiment. As an illustration of the PLUG-calorimeter response to selected low-Q^2 events the distribution of the total energy is shown in Figure 37. It compares remarkably well with MC-simulations produced using the Colour Dipole Model (LEPTO 6.1 MEAR, see reference [104]).

3.4 The tail catcher (TC)

In order to measure the hadronic energy leaking out of the LAr calorimeter and BEMC, eleven of the sixteen limited streamer tube (LST) layers of the instrumented iron are equipped with readout electrodes (pads, see also Section 4). Here we describe the features of the LST tail catcher (TC) relevant for the energy measurement which is based on the analog readout of the pad signals. For more details see reference [105].

The pad sizes vary from 28×28 cm^2 in the endcaps up to about 50×40 cm^2 in the barrel region. The pad signals from the five inner (six outer) layers are summed up by tower builders (TB) to form the front (back) tower signals. The differential analog signals from the TB's are then relayed in groups of 12 to the cable stations (CS) which reorganise the signals from the towers into groups of 16. From there the signals are sent to the analog superboards (SB) whose function is to amplify, integrate and store the analog signals in groups of 128 channels each. The geometry of the tower structure is briefly described in Table 10.

Region	θ range	Segmentation	# of channels
Forward end cap	$6° \leq \theta \leq 33°$	x and y	552
Central barrel	$33° \leq \theta \leq 137°$	ϕ and z	2784
Backward end cap	$137° \leq \theta \leq 172°$	x and y	552

Table 10: Layout of the pad readout of the iron instrumentation.

3.4.1 Electronics

The amplifier used on the TB-boards allows for the measurement of single muons as well as hadronic showers without saturation. The signals have a dynamic range of 0.75 mV to 1 V. Each superboard accepts the input of 128 channels which are individually processed by a line receiver, shaper and sample & hold. The line receiver and shaper are modified versions of the LAr calorimeter system cards, while the sample & hold cards are identical to those used in the LAr readout system. The signals are multiplexed and held in the output buffer to be read by the analog receiving unit (ANRU). The data are then zero suppressed and corrected in the DSP and read out (see Section 3.1.6).

The calibration of the superboards is done by sending calibration pulses through the analog readout chain beginning at the tower builder board. The calibration constants are downloaded into the DSPs to correct for the channel to channel variations and non-linearities. Channel to channel variations are less than 2% for 3888 channels .

During data taking and calibration, acquisition is controlled by the LAr calorimeter OS9 system. Normal data and calibration results can also be collected in stand-alone mode, in which case the local TC test station is used.

3.4.2 Energy calibration

The conversion of the signal charge Q_i, as measured in a tower i, to hadronic energy $E_{had,i}$ is given by [106]:

$$E_{had,i} = c_1 c_{3,i} \frac{Q_{had,i}}{c_2}$$

The general hadronic energy calibration constant c_1 has been determined in test measurements at CERN using pion and muon beams [107]. The parameter c_2 gives the tower charge of an average minimum ionizing particle, i.e. a muon, at an angle of incidence of 0° with respect to the normal of the LST chambers. The intercalibration factor for each tower, $c_{3,i}$, describes the tower to tower variations of the measured charge.

The constant c_1 is derived from the linear relationship between the incident pion energy and the ratio Q_π/Q_μ of the measured charge for pions and muons. Defined in this way c_1 is essentially determined by the sampling fraction of the calorimeter and the gas used in the chambers. It does not depend on the angle of incidence of the hadrons and is also insensitive (in wide limits) to the operating conditions [107]. The parameter c_2 and the charge $Q_{had,i}$ on the other hand vary with high voltage, pressure, gas composition and temperature. Since the atmospheric pressure is the only one of these operating parameters which can change rather quickly, we compensate for this effect by regulating the high voltage (see section 4.1.3 of the muon system).

The transformation of ADC counts into charge is done online during the readout process according to

$$Q_i = p_{1,i}(ADC_i - p_{0,i})$$

The pedestals $p_{0,i}$ are obtained from random triggers and the gains $p_{1,i}$ are given by the slope of the test pulser response curves of the electronic calibration. Both varied by < 2 % over the whole data taking period. Zero suppression allows to read out only pads above a certain threshold.

The parameters c_2 and $c_{3,i}$ are determined from cosmic muons [108], triggered by opposite pairs of barrel or endcap modules in special cosmic runs. The data have to be corrected for non-normal incidence with respect to the chamber plane. In order to keep the corrections small, only tracks with $\tan\theta < 0.8$ are considered in the calibration procedure. The intercalibration constants $c_{3,i}$ vary by $\sim 10\%$ within one module. There are larger module to module variations depending on the module location in the iron yoke, mainly due to different gas temperatures and pad sizes.

3.4.3 Performance

The performance of the tail catcher has been studied in test measurements at CERN with π and μ beams of 10 to 80 GeV [107]. The energy response for single pions is linear up to at least 40 GeV and the energy resolution is $\sigma/E \simeq 100\%/\sqrt{E}$.

The calibration of the tail catcher at HERA is done by cosmic muons as described above and taking the energy scale from the CERN test results as $c_1 = (0.233 \pm 0.002)$ GeV. Figure 38 shows representative muon spectra of a complete module for the inner and outer towers. Clean muon signals can be seen with mean values far beyond the pedestals. The widths relative to the most probable values are ~ 35 %. The ratio of the mean values of inner and outer towers corresponds to the expected value of 0.8. We do not observe any effect of the magnetic field in the iron yoke on the muon signal. The intercalibration constants vary among the detector by $\sim 20\%$ (mostly due to a vertical temperature gradient within H1) with a long term stability of $\sim 10\%$. They are regularly measured with cosmic muons.

Important for energy measurements with the H1 detector is the combination of the tail catcher with the LAr calorimeter. The energy response can be symmetrized and the energy resolution can be improved by including the information of the tail catcher [66, 90, 72]. Corrections for energy losses in dead materials have to be done for each event. Inside the tail catcher dead material appears as cracks between towers, in particular in the transition region between the end cap and barrel yoke. Corrections between adjacent towers are calculated using the ratio of the tower areas with and without the crack as correction factor. More involved corrections are necessary for the material between the calorimeters, e.g. the cryostat wall and coil between the LAr calorimeter and the TC. For this purpose a hadronic object in the LAr calorimeter is geometrically linked with a TC cluster into a generalized cluster. The energy losses are estimated [90] by a linear interpolation of the energy deposit in the last layer of the LAr calorimeter $E_{LAr;last}$, and the first layer of the tail catcher, $E_{TC,first}$:

$$E_{loss} = \alpha(\theta)(E_{LAr,last} + 0.5E_{TC,first})$$

The calculated energy loss is distributed among the cells in proportion to their energy contents. The function α depends on the polar angle θ of the shower or, more precisely, on the thickness Δt_{dead} of the material between the two calorimeters and are almost independent of the energy over a large range. It has been determined as a function of Δt_{dead} from dedicated test measurements at CERN [90]. At H1 Δt_{dead} varies from 0.5 up to 2.4 interaction lengths depending on the polar angle θ. The corresponding values for α range from 0.1 up to 1.1. The uncertainty of the energy correction was estimated to $\sim 20\%$. Figure 29 shows the effect of the combined LAr and TC measurements with energy loss corrections from test beam results.

Calibration and correction procedures have been successfully transferred from the test beam measurements to the H1 detector at HERA, where the balance of the transverse hadronic energy p_{th} and the transverse electron energy p_{te} in neutral current events can be used to check the overall hadronic calibration. Figure 39 shows the ratio $\mathrm{p}_{th}/\mathrm{p}_{te}$ of p_{th} as measured with the hadronic section of the LAr calorimeter and the TC (including the above mentioned corrections) and p_{te} as measured with the electromagnetic section of the LAr (or BEMC) versus the energy fraction deposited in the TC. The distribution is flat, demonstrating that calibration and corrections have been treated properly.