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 MΩ / $\square$, 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 ≈ 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^{exp}_{EMC}, c^{exp}_{HAC}) were determined for each wheel, which transform the measured electric charge Q_i per cell into energy deposited by electron showers. Corresponding constants (c^{MC}_{EMC}, c^{MC}_{HAC}), 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^{exp}_{EMC} 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:

$$E^{exp}_{rec} = c^{exp}_{EMC} \sum_{i}^{EMC} Q_i = E^{MC}_{rec} = c^{MC}_{EMC} \sum_{j}^{EMC} E^{vis}_j \tag{1}$$

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