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 ($\theta \approx 0.6\ ^\circ$) and the forward part of the LAr calorimeter ($\theta \approx 3.5\ ^\circ$). 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