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.