Performance of the ATLAS Liquid Argon Barrel Calorimeter in the 2004 Combined Test Beam

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Abstract. The combined test beam (CTB) of a full barrel slice of the ATLAS detector in 2004 offered a unique opportunity to study the combined performance of the various sub-detectors down to energies as low as 1 GeV. In addition new analysis tools and techniques were developed that are already being used by the ATLAS offline reconstruction. This work presents studies related to the electromagnetic (EM) barrel calorimeter, both standalone and combined with the tracking and hadronic detectors. It also presents how these developments can be transferred to the ATLAS experiment. Here emphasis is given on studies of material effects on the electron energy reconstruction. The presence of extra material in front of the EM calorimeter leads to non-linear and non-uniform calorimetric energy response that requires detailed studies of sophisticated calibration methods. In this work we discuss these EM calibration methods and their application on the CTB data analysis. We also present final results on EM calorimeter uniformity, linearity and resolution for high energy beams (from 9 to 250 GeV), and studies of Monte-Carlo description of the calorimeter response at very low energies (from 1 to 9 GeV).

1. Introduction

ATLAS is a general purpose experiment mainly aimed at the discovery of the Higgs boson. From the collision point outwards it consists of a tracking detector, an electromagnetic and hadronic calorimeter and a muon spectrometer. The tracking detectors are operated within a magnetic field collinear to the beam axis. This configuration was reproduced in 2004 where a full barrel slice (from the innermost tracking detectors and magnetic field to the outermost muon spectrometer) was exposed to particles ranging from 1 to 350 GeV. The setup of the test beam was kept as close as technically possible to the ATLAS geometry. The distance between sub-detectors, the pointing geometry and the magnetic field orientation were preserved when permitted. The most important goals of this test beam campaign were the following:

- Test the detector performance with final or close to final electronics equipment, data acquisition (TDAQ) infrastructure and reconstruction software.
- Validate the description of the data by Monte-Carlo (MC) simulations down to energies of 1 GeV to prepare the simulation of the ATLAS data.
- Perform combined studies in a set-up very close to ATLAS (e.g. combined calorimetry, and ID-calorimetry).

In the following, after a description of the testbeam setup, we then focus on the energy reconstruction and calibration of electrons leading to the final results on linearity, uniformity and resolution (down to 9 GeV) for different material configurations. Subsequently we study the
material dependence of the ratio of the energy deposited in the first sampling over the energy deposited in the second sampling as a possible way to correct for extra material in front of the calorimeter in ATLAS. The last sections cover the very low energy (1 to 9 GeV) electron studies, the E/p measurements and the Bremsstrahlung recovery studies in magnetic field.

2. Description of the setup
Fig. 1 presents a schematic view of the setup which is described in detail in [1].

![Figure 1](image)

**Figure 1.** Schematic view of the H8 CTB setup, including the inner detector components and the LAr and Tile calorimeters.

The tracking part consists of a silicon pixel detector, a silicon strip detector (SCT) and a transition radiation tracker (TRT). Both pixel and SCT modules are installed in a magnet providing a field along \( z \), as in the ATLAS detector. The TRT detector is not in the field (in ATLAS, the TRT detector is inside the solenoidal field). The orientation of the 1.4 T magnetic field is horizontal as in ATLAS, to get a vertical displacement. The deviation in the field for 10 GeV electrons is \( \approx 11 \text{ cm} \) at the front of the electromagnetic calorimeter. In ATLAS, a 10 GeV electron produced at the vertex deviates by \( \approx 13 \text{ cm} \). The two calorimeters (electromagnetic and hadronic) are installed on a movable table which can rotate in \( \eta \) and translate in \( z \) and \( x \). It is not possible to rotate in azimuth \( \phi \). The electromagnetic calorimeter modules were built for the ATLAS Combined Run, using lead sheets, electrodes, motherboards, connectors and cables left from the production of the 32 ATLAS barrel modules. The geometry of such a module has been extensively described in [5].

3. The energy reconstruction in the electromagnetic Calorimeter
The ionisation signal generated in the calorimeter is collected from the read-out electrodes and brought via cables to the front end electronics where it is amplified, shaped and sampled at a 40 MHz frequency. The samples are then stored in an analog pipeline until the trigger decision. The digitised samples are then transmitted by the calorimeter back-end electronics and the signal amplitude is reconstructed and converted to MeV. Once the cell energies are reconstructed, these cells are then summed to form a cluster over all three longitudinal compartments and the presampler of the EM calorimeter. A simple projective cone algorithm, optimised for the measurement of EM showers, was used. Starting from the cells of the middle layer, the most energetic cell is taken as a seed of the cluster and a fixed window of \((\Delta \eta \times \Delta \phi) = 0.075 \times 0.075 \) (3x3
in middle cell unit) is opened around the seed. The choice of the cluster size is a compromise between electronic noise and shower containment.

The initial electron energy is found by performing a linear weighting of the longitudinal sampling energies which build up the cluster [2]. This MC based calibration procedure makes use of the longitudinal segmentation of the calorimeter and is described by the relation:

\[ E_{\text{particle}} = \text{offset} + W_0 \times E_0 + \lambda \times E_{\text{acc}} + W_3 \times E_3 \]  

(1)

where \( W_i \) and \( \lambda \) are the weighting factors that are to be determined. \( E_i \) is the measured energy in sampling \( i \) within the \( 3 \times 3 \) cluster and \( E_{\text{acc}} = E_1 + E_2 + E_3 \). Each term of the calibration scheme is described as follows:

- **offset + \( W_0 \times E_0 \):** this term parametrises the energy lost in the passive material before the presampler and between the presampler and the first layer of the EM calorimeter versus the energy deposited in the presampler. The purpose of the presampler is to measure the multiplicity of an early showering electromagnetic particle. The energy lost by pre-showering electrons is proportional to the presampler energy and is parametrised by the \( W_0 \) factor. The offset is due to residual energy loss through ionisation in the case of hard bremsstrahlung where the resulting photon does not interact in the presampler.

- **\( \lambda \times E_{\text{acc}} \):** this term corrects for the energy lost outside of the cluster, it includes an implicit dependence of the sampling fraction with energy as shown in figure 2. This correction factor can be obtained by the ratio of the cluster energy by the total energy deposited in the calorimeter as can be seen in figure 2. Typically the leakage outside the cluster of about 5% of the energy deposited in the accordion of the EM calorimeter.

- **\( W_3 \times E_3 \):** a correlation exists between the deposited energy in the back sampling and the energy leaking from the back of the calorimeter. This factor can be obtained by parametrising the energy lost behind the calorimeter as a function of the energy deposited in the back layer of the calorimeter.

![Figure 2. Sampling fraction versus the electron energy (left). Fraction of the energy measured within the cluster in the calorimeter (right)](image)

4. **Beam energy measurements**

The electron momentum selection is based on a spectrometer consisting of two collimators and two triplets of bending magnets. The beam momentum is related to the bending angle and the
integral of the magnet field along the beam path through the formula, \( \Delta \theta = 0.3 \frac{\int B dl}{P} \), where \( P \) is the beam momentum in \( \text{GeV}/c \), \( \Delta \theta \) is the bending angle and \( \int B dl \) is the bending power. The bending power is a function of the current applied to the magnets, thus the beam momentum is deduced from these currents. The energy lost by electrons due to synchrotron radiation was estimated and subtracted. Also the shift of the mean beam momentum due to non-centered collimators was studied through a simulation of the beam line and corrected. There is an error on the absolute energy scale of up to 1.0% coming from geometrical uncertainties. For uniformity and linearity measurements, high precision should be achieved on the relative beam energy measurements. Assuming that the beam conditions do not change from run to run, the only uncertainty on the relative beam energy comes from the uncertainty on the measurements of the currents in the bending magnets and on the uncertainty in the remnant field. In summary, a total precision of 0.2% is achieved at low energy (20 GeV).

5. Comparison between Data and Monte-Carlo Simulation

The ATLAS calibration strategies rely heavily on the simulation of the experimental test-beam setup and the detector response. Thus it is important to study the level of agreement between data and MC prediction of the total energy distribution, the energies measured in each layer, their correlations, and the lateral development of the EM shower. Difference in the lateral and longitudinal shower profiles between data and MC may have significant effects in linearity due to the partial containment of the shower energy when a fixed cluster size is used. The longitudinal segmentation of the barrel calorimeter in four compartments allows for an evaluation of the simulation performance. The main goal of such an evaluation is to extract the level of agreement between the simulation of EM response and the response seen in the data. The level of agreement between data and MC in the reconstructed energy is at the level of 0.5%, consistent with the total expected systematic uncertainty discussed below.

The level of description of the EM shower development in the LAr Calorimeter is obscured by the presence of uncertainties associated with the accuracy of the detector description (thickness of the lead absorbers, the depth of the first sampling, the exact amount of material in front of the first sampling cables-electronics, the thickness of the cryostat and the amount of LAr in front of the presampler). The same uncertainties will be an issue during the actual ATLAS data taking, so their study in a controlled environment is important. All these uncertainties were extensively studied in the combined test beam and a cumulative systematic error in the level of agreement between data and MC from all effects of the order of 0.2-0.3% could be deduced.

6. Results on linearity and resolution

The energy linearity obtained after application of the longitudinal weights to the cluster sampling energies is summarised in Figure 3 for 4 different material configurations in front of the calorimeter cryostat: no material, 25, 50 and 75mm of Aluminium. From the figure a 0.5% non-linearity is observed. However a much smaller spread of the data-points at the level of 0.2% or less is seen for fixed beam energy. The variations from one energy point to another can be attributed to the systematics of the CTB setup itself. In particular, changes to beam conditions (collimator openings, beam-optics magnetic fields) seem to have large effects in the relative beam energy. In the case where the beam conditions are unchanged, as in the case of the 180GeV beam in Figure 3, a very small variation is observed.

The corresponding energy resolution for the 4 material configurations is presented in Figure 4. From the figure a good agreement between the data and MC points can be seen. The resolution worsens at the approximate rate of 0.5%/\( \sqrt{E} \) per 30%\( X_0 \) increment of the material in front of the calorimeter.
Figure 3. Energy Linearity after calibration for four different material configurations in front of the calorimeter: no material (black triangles), 25mm Al (red circles), 50mm Al (blue circles) and 75mm (black rectangles).

Figure 4. Energy resolution after calibration (using calibration hits) from Period 5 data and for 4 different material configurations in front of the calorimeter: no material (top left), 25mm Al (top right), 50mm Al (bottom left) and 75mm (bottom right).
7. **Results on the uniformity of the calorimeter response**

The uniformity of the calorimeter energy response depends on the impact point position within the cell. The cluster $\eta$ position is determined from the barycenter of the energy deposition in the second sampling. The cluster size is a multiple of the size of a single cell. Consequently, the energy leakage outside the cluster is a function of the incoming particle impact coordinate within the cell. The measured energy is maximal when the impact point is in the center of the cell and drops by about 1% at the border of the cell.

The cluster energy also depends on the impact point within the cell along the $\phi$ direction due to the accordion geometry: the incident electrons traverse more passive material in the accordion fold than in the straight section due to the rounded shape of the folds and thus deposit more energy. There is an additional effect due to lateral leakage which is due to the limited cluster size (in $\phi$), similar to the already mentioned modulation in $\eta$.

The High Voltage (HV) system of the electromagnetic calorimeter is divided in $\Delta\eta \times \Delta\phi=0.2 \times 0.2$ regions (the so-called sectors). During the combined test beam the top side of one electrode had decreased HV, however the bottom part had the nominal HV of 2000 V. Thus the energy measured in the cells belonging to the $\eta$ region covered by this electrode has to be corrected.

Figure 5 gives the final result on the uniformity of the EM calorimeter. A uniformity level of 0.5% was observed.

![Figure 5. Uniformity of energy response of the EM calorimeter for 180 GeV electrons](image)

8. **Material effects and E1/E2**

The ratio of the energy response in the strips and the middle sections of the EM calorimeter is sensitive to the material distribution in front of the calorimeter. This is demonstrated in figure 6, where the ratio is plotted for the runs where extra amounts of material (in steps of $0.3X_0$) were placed in front of the calorimeter. A significant shift in the mean and shape of these distributions is observed. The increase in the mean of the data distributions by 20-25% for $0.3X_0$ is well reproduced by the MC. In figure 6 the mean of these $E1/E2$ distributions are shown as a function of the amount the extra material. This material dependence can be used to extract the calibration constants shown in Equation 1 from data instead of relying on the MC description. By unfolding the energy dependence of $E1/E2$ as well as the energy dependence of the weights, the direct dependence of $E1/E2$ on the material, and hence the weights can be derived. Application of such a strategy to the CTB data led to a determination of the “offset” and $W0$ constants with an accuracy better than 5%.
3x3 cluster E1/E2 (E=100GeV)

0 0.2 0.4 0.6 0.8 1 1.2
0
0.02
0.04
0.06
0.08
0.1
0.12

0 0.0 X
0.2 X
0 0.3 X
0 0.6 X
0 0.9 X

Figure 6. (left) Ratio of the energy response in the strips and the energy response in the middle sampling, E1/E2, for various thicknesses of material in front of the calorimeter cryostat and for electron energy of 100 GeV. Data are denoted by markers and MC by histograms. (right) Mean of E1/E2 distribution vs material thickness in front of the calorimeter cryostat.

9. Very low energy studies (1-9 GeV)
During 2003 a very low energy (VLE) beamline was built as part of the H8 beam line. Particles from the HE beamline are diverted onto an additional target (T48), and a spectrometer consisting of 4 dipole magnets selects particles of the desired momentum. The precise momentum measurement is obtained from the deflection angle that is measured from the position of the beam spot in beam chambers placed before and after the magnets of the spectrometer. The estimated uncertainty on the beam energy comes from the uncertainty on the angle measurement due to the spatial resolution of the beam chambers (≈ 0.2 mm) is 0.35 %. In addition, a systematic uncertainty of 1.5 % has to be taken into account due to the uncertainty of the alignment of the beam chambers and the exact position of the B8 magnet. The calibration strategy for the very low energy is similar to that of the high energy electrons. One difference lies in the fact that the weights have a strong sampling fraction dependence that need to be taken into account. In Fig. 7 the comparison of the energy responses of the the four calorimeter compartments is shown for 5 GeV electrons. A detailed description of the calibration scheme for the very low energy electrons can be found here [6].

10. E/p measurements and Bremsstrahlung recovery
A number of studies on the combined performance of the inner detector and the electromagnetic calorimeter are ongoing. A quick overview of the main studies and their implications for ATLAS is given below:

- The energy distribution in the calorimeter and the $p_T$ distribution in the inner detector can be parametrised and the convolution describes well the E/p distributions. A method has been developed to extract the energy scale for the EM calorimeter and the method can be used to compare the inner detector and LAr EM scales in ATLAS.
- A Bremsstrahlung recovery algorithm has been developed for ATLAS and tested successfully on the combined test beam. The implementation of the algorithm consists of dividing the (silicon detector) track into two parts, and refitting only the part close to the vertex together with the LAr cluster position as an ordinary hit.
Figure 7. Layer energies comparing Monte-Carlo simulation (filled histograms) and data (black circles) for 5 GeV electrons

11. Conclusions
In this work final results on energy linearity, uniformity and resolution of the ATLAS barrel liquid argon electromagnetic calorimeter were presented. The calorimeter response was found to be linear at the level 0.5% limited by test beam systematics. The stochastic term of the resolution is around 10%/\sqrt{E} and the uniformity is at the level of 0.5%. These results are consistent with earlier test beam studies ([3],[4]). Although the calibration presented here is MC based, the calibration constants can be tested with data. Observables like the E1/E2 ratio of response between the first and the second longitudinal layers of the calorimeter are very sensitive to the calibration constants can be tested with data. Observables like the E1/E2 ratio of response between the first and the second longitudinal layers of the calorimeter are very sensitive to the upstream material excesses or deficits. This ratio was used to extract the calibration constants directly from the test beam data. The calibration procedure presented here was also applied to very low energies (1-9GeV) where a very good agreement between data and MC was observed.

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