Performance of the ATLAS forward calorimeter

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Abstract. The ATLAS forward calorimeter is a liquid argon calorimeter based on a novel tubular electrode structure. This paper will focus on the performance of the calorimeter for electrons and hadrons, based on the analysis of beam test data taken in the H6 beamline at CERN in 2003. The ATLAS requirements on the forward calorimeter performance will be reviewed, the calorimeter design and construction will be discussed, and the performance for electron and hadrons will be described.

1. The ATLAS Forward Calorimeter

The Large Hadron Collider (LHC), located at CERN, is the highest energy collider built to date. It will collide together protons at a center of mass energy of 14 TeV at four points around the 27 km LHC ring. ATLAS is a detector located at one of these four collision sites. ATLAS is made up of several subsystems, used to measure the products of the proton-proton interactions. The main subsystems of ATLAS include the liquid argon and tile calorimeters, muon spectrometers, inner detectors, forward luminosity detectors, toroid and solenoid magnets.

The ATLAS detector is designed to have hermetic calorimetric coverage to provide a good measurement of jet energy and missing transverse energy. The calorimetric coverage spans $|\eta|$ of 0 to 4.9. At the highest $|\eta|$ range (3.1 < $|\eta|$ < 4.9) sits the liquid argon Forward Calorimeter (FCal). It is housed within the endcap cryostat, between the hadronic endcap calorimeter and the beam pipe. The location of the FCal within ATLAS is shown as one of the lightly shaded regions around the beam pipe in Figure 1.

Each FCal endcap is composed of three modules: FCal1, the electromagnetic calorimeter with copper as its main absorbing material, is closest to the interaction point. This is followed by FCal2 and FCal3, the hadronic calorimeters, using tungsten as their primary absorbing material. Each module has a longitudinal depth of approximately 45 cm, an inner radius of approximately 8 cm and an outer radius of approximately 45 cm. Detailed information about the design and construction of the FCal can be found in [1].

The LHC is designed to have a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ and a bunch crossing frequency of 40 MHz; resulting in an outward going flux of high energy particles. The high radiation and high frequency of collisions puts design constraints on each subdetector. For the liquid argon subsystem this implies a requirement of radiation hard material, and fast signal collection in the active medium. The FCal electrodes are composed of an inner anode rod surrounded by a cathode tube. The rod and tube are held at a potential difference of 250 V for FCal1 (375 V for FCal2, and 500 V for FCal3), and are filled with the active liquid argon medium. The liquid

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arg on gap is 269 µm, 376 µm, and 508 µm, in FCal1, FCal2, and FCal3, respectively. This small gap is necessary to provide fast signal collection, and reduce ion buildup that could alter the electric field across the gap.

The unique aspect of this calorimeter is that these electrodes run parallel to the beam pipe. Figure 2 shows the front face of FCal1 as viewed from the interaction point down the beam pipe. In this figure the rod and tube structure are clearly seen. In FCal1 four electrodes are grouped together to form an electrode group (in FCal2 and FCal3 this number is six and nine electrodes). Then typically four such electrode groups are summed together to form a readout channel; this is referred to as a cell in this paper.

2. Forward Calorimeter Test Beam Setup
A test beam was performed in 2003 with the CERN SPS H6 beamline to calibrate the FCal. The main goals of the test beam were to measure the intrinsic response of the calorimeter to electrons and hadrons, examine its performance under ATLAS-like conditions, and to understand the energy loss down the beam pipe and splashing across the beam hole. To achieve these goals, beams of electrons and hadrons with energies from 10 to 200 GeV were directed into one of the final FCal assemblies.

A schematic of the beamline is shown in Figure 3. The particles enter from the left, leaving the bend 9 magnet (B9). They traverse six beam profile chambers (BPCs), which provide tracking in the x and y directions. There are three scintillators (S1, S2, S3) that are used for coincidence triggering, and a veto wall, all to remove multiple scattered particles. The FCal sat in a cryostat filled with liquid argon. Downstream of the FCal were additional scintillators; a muon counter used to remove muons from the electron beam, and a tail catcher made of alternating steel and scintillator layers also used in the beam cleaning procedure.

A wide beam spot was used to ensure even sampling across the front face of the FCal. Five impact points on the front face of FCal1 were targeted; these are shown in Figure 4. For each
impact point the FCal was rotated and translated such that the incoming particles hit the FCal as if they were coming from the ATLAS interaction point. The positions labelled 4H and 4L were chosen to fully contain particle showers. They differ in the amount of upstream material: position 4L had a minimal amount of upstream material to understand the intrinsic response of the FCal, whereas position 4H had additional material in front to simulate the ATLAS environment. The positions labelled 1, 2, and 3 were taken to study the detector response at the inner edge along the beam line.

3. Data Analysis of Impact Position 4L
This section describes the analysis of the electron and hadron data taken at the impact position labelled 4L. In this position there was minimal upstream material and particle showers were fully contained. This allows calculation of the intrinsic response of the FCal, which includes the energy resolution for electrons and hadrons, determination of the electromagnetic scale, and tests of different hadronic weighting schemes and clustering algorithms.

The pedestals and noise were calculated on a run-by-run and channel-by-channel basis using pedestal data taken during each run. The physics signal was reconstructed using the optimal filtering technique [2]. Seven samples were taken every 25 ns to reconstruct the pulse in each channel.
The electron and hadron data were clustered in the FCal using a cylindrical clustering algorithm. The cluster center was defined as the projection of reconstructed tracks using the BPCs. From the cluster center the energy of all cells within a fixed radius were summed. For the electron data analysis all cells within an 8 cm radius in FCal1 were used, and for the hadron data all cells within a 16 cm radius in FCal1, FCal2, and FCal3 were summed.

3.1. Electron Analysis of Impact Position 4L

Electron data were taken for eight beam energies between 10 and 200 GeV. A sample distribution for the 100 GeV data is shown in Figure 5. Similar distributions exist for the other seven energy points. The horizontal axis of Figure 5 is in units of ADC counts to set the electromagnetic scale. For each energy point the electron peak is best fit with a double Gaussian; it best describes the central peak and small high energy tail which is present due to the slight impact point dependence of the response. The primary background in the electron data sample was pion contamination. To properly account for the high energy tail of the pion distribution leaking under the low energy tail of the electron distribution, the pion background is modeled using pion data taken at the same energy, this modeling is shown on Figure 5 as the dashed line. The full fit to the double Gaussian and pion background is shown with the solid line. The mean and variance of this fit are used in the calculation of the linearity and energy resolution.

The electron linearity which is the mean reconstructed energy, in ADC counts, as a function of beam energy, is shown in Figure 6. The data are fit to a straight line, where the slope and intercept are free parameters. The best fit to the data yields a slope of $12.07 \pm 0.7$ (stat) $\pm 0.7$ (sys) ADC/GeV, and an intercept of $-12.27$ ADC which is attributed to upstream energy losses, corresponding to a loss of approximately 1 GeV. Using the known properties of calorimetry one can calculate the electromagnetic scale for each module. This scale for each FCal module is predicted to be:

$$\alpha_1 = 12.0 \text{ ADC/GeV} \quad \alpha_2 = 6.1 \text{ ADC/GeV} \quad \alpha_2 = 5.4 \text{ ADC/GeV}$$

(1)

The results presented in this paper agree with the prediction for FCal1, and a previous FCal test beam has confirmed the predicted electromagnetic scale of FCal2 relative to FCal1 [3].

![Figure 5](image.png)

**Figure 5.** The double Gaussian fit and pion modeling to the 100 GeV electron data (plotted in ADCs). The electron peak is fit with a double Gaussian. The pion modeling is shown with dashed lines, and the full fit is shown with solid lines.

Studies were performed to quantify systematics arising from choice of binning, fitting technique, and cylinder cluster radial size. These sources were found to have a small impact on the overall linearity and energy resolution, contributing to an overall systematic of $\pm 0.1-0.2\%$. The data is linear to within $\pm 0.8\%$ down to 10 GeV.

The intrinsic electron energy resolution can be found using the position 4L data. The electronic noise was not constant between runs due to a configuration problem, and so the noise is subtracted in quadrature energy by energy. This noise is calculated by clustering the
same cells as those in the physics data, event-by-event but using the random data, and fitting the resulting energy distribution over all runs of a given energy point to a single Gaussian. On average the electronic noise clustered with the 8 cm cylinder cluster in FCal1 is 1 GeV. The noise-subtracted energy resolution is shown in Figure 6, where the data points at each energy are the solid points. These data points are fit to the energy resolution function:

\[
\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2}
\]  

(2)

where \(a\) is the stochastic term describing the statistical variations in the shower development, and \(b\) is the constant term accounting for detector irregularities and miscalibrations. The best fit values for these two parameters are a stochastic term \(a = 28.5\% \cdot \text{GeV}^{1/2}\) and a constant term of \(b = 3.5\%\).

\[\text{Beam Energy [GeV]}\]
\[\text{Reconstructed Energy [ADC]}\]

\[\text{Resolution } \sigma_E [\%]\]

\[\text{Beam Energy [GeV]}\]

**Figure 6.** The left figure shows the electron linearity of the mean reconstructed energy versus beam energy. The data are the solid points and the dashed line shows the best fit line to the data, used to set the electromagnetic scale of FCal1. The figure on the right shows the electron noise-subtracted energy resolution at impact position 4L.

### 3.2. Hadron Analysis of Impact Position 4L

The FCal is a non-compensating calorimeter, as such it is necessary to apply a software correction to properly reconstruct the energy deposited by hadrons. This calibration has been performed with two techniques. The first is a longitudinal weighting scheme, in which there is a calibration constant for each module. These three constants are extracted by minimizing the energy resolution and requiring that the beam energy equals the mean reconstructed energy:

\[E = A_1 \alpha_1 E_1 + A_2 \alpha_2 E_2 + A_3 \alpha_3 E_3\]  

(3)

where \(A_i\) (\(i = 1,2,3\)) are the longitudinal weights, referred to as flat weights, \(\alpha_i\) are the electromagnetic scale factors as predicted from first principles (Equation 1), and \(E_i\) are the summed energies in FCal1, FCal2, and FCal3, respectively.

The second weighting scheme takes advantage of both the coarse longitudinal and fine transverse segmentation of the FCal, and is referred to as the radial weighting technique. The cluster center, as calculated using the projection of the BPC tracks, is taken as the starting point of this calibration. Going out with increasing radius from the cluster center the cells are split into radial slices. In this analysis 16 radial slices are taken at 1 cm each for each FCal
module. The $16 \times 3$ radial weights are fit by minimizing the energy resolution at each point:

$$E = \sum_{i=1}^{3} \sum_{j=1}^{16} \sum_{k=1}^{n_{\text{cells}}} W_{ij} \times C_{ijk}$$  \hspace{1cm} (4)$$

where $i$ is the sum over the three FCal modules, $j$ is the sum over the 16 radial slices, and $k$ is the sum over all the cells in that radial slice. The $W_{ij}$'s are the 16 radial weights for each of the three FCal modules, and the $C_{ijk}$ are the energy in the $k$th cell in the $j$th slice of the $i$th FCal module at the electromagnetic scale. The number of cells the $j$th radial slice of the $i$th FCal module is defined as $n_{\text{cells}}$.

The flat weights and radial weights extracted at the 200 GeV energy point are applied to all data to avoid energy dependent weights. Once applied one gets the energy resolution points shown in Figure 7. As in the electron analysis the noise has been subtracted in quadrature at each energy point. The average noise clustered in the 16 cm cylinder cluster using the flat weights is 5.5 GeV. These points are then fit to the noise subtracted energy resolution function, Equation 2. The fit results for the stochastic and constant terms for the two weighting techniques are shown in Table 1. The radial weights use more information from the calorimeter, and take advantage of the unique design of the FCal, hence provide a better performance than the flat weighting scheme.

![Figure 7. Hadronic energy resolution at impact position 4L. The 200 GeV flat weights and radial weights have been applied to the data. The noise-subtracted energy resolution function is shown as the solid line fit to the data of each weighting scheme.](image)

| Weighting Technique | Stochastic Term [%·GeV\(^{1/2}\)] | Constant Term [%] |
|---------------------|-----------------------------------|------------------|
| Flat Weights        | 95.3 ± 0.6 (stat)                 | 7.52 ± 0.06 (stat) |
| Radial Weights      | 70.0 ± 0.7 (stat)                 | 2.97 ± 0.10 (stat) |

The largest source of systematic uncertainty in the hadron analysis is the choice of hadronic weights applied to the data. The results presented here apply the flat and radial weights extracted with the 200 GeV hadron data, the highest energy data available in the test beam. In the flat weight analysis if instead the weights extracted at 100, 120, and 150 GeV are applied to the data one would find a variation of $\pm 1.6\%$·GeV\(^{1/2}\) in the stochastic term and $\pm 0.4\%$ in the constant term.
4. Ongoing Analyses

There are several ongoing analyses using the FCal test beam data. The results presented above show the response of the FCal at impact position 4L with a cylindrical clustering algorithm, and application of flat and radial hadronic weights to the hadron data. Analyses are underway to redo this analysis with alternative clustering algorithms that are used in ATLAS. Comparisons are being made to Monte Carlo simulations of the test beam with various physics models. There are four additional impact points that are currently under investigation (these were shown in Figure 4). A comparison of the 4H and 4L will show the effect of upstream material on the FCal performance. The inner edge analysis uses the data taken at impact positions 1, 2, and 3, to examine energy loss and splashing across the beam pipe.

Preliminary results of the test beam analysis using one of the default ATLAS clustering algorithms is presented below. This is followed by a first look at the energy loss in the vicinity of the beam pipe with data taken from impact positions 1, 2, and 3.

4.1. Topological Clustering

Topological clustering is one algorithm used by default in ATLAS to find significant sources of energy deposition in the liquid argon and tile calorimeters. The cylindrical clustering technique as described in this analysis cannot be used for the FCal in ATLAS because there is no tracking in front of the FCal necessary to set the cluster center. The topological clustering algorithm is based on the significance of a cell’s energy divided by its noise, the significance is defined as $\sigma$. By default in the FCal, a cluster is seeded by a cell if the cell has a $4\sigma$ significance. A cluster is expanded upon by examining the significance of neighboring cells. In the default configuration, a neighbor cells must have a $2\sigma$ significance to expand the cluster. The last configurable option is the cell significance of the cells that are neighbors to an existing cluster. If the significance is greater than the set value (the default is $0\sigma$), the cell is included in the cluster. The default topological clustering configuration is: seed/neighbor/cell = $4\sigma/2\sigma/0\sigma$.

Using the default topological configuration and repeating the analysis as before on electrons in the 4L position, the best fit line yields an electromagnetic scale in FCal1 of 12.11 ADC/GeV, which agrees with the cylindrical clustering results of 12.07 $\pm$ 0.7 (stat) $\pm$ 0.7 (sys) ADC/GeV. The noise subtracted energy resolution has fits for the sampling and constant terms of 31.8% $\cdot$ GeV$^{1/2}$ and 3.3%, respectively. These results are comparable to the results using the cylinder clustering, and confirm the use of the topological clustering algorithm for use in the FCal.

Studies are ongoing to optimize the topological clustering algorithm with both the electron and hadron data.

4.2. Inner Edge

The inner edge impact positions are labelled as 1, 2, and 3 in Figure 4. The primary goal of these data are to examine the energy loss down the beam line and energy splashing across the beam pipe. For these positions only 200 GeV electron and hadron data are available; in the future Monte Carlo simulations will be necessary to study this effect at a range of energies. Clustering is done with the topological clustering algorithm with the default seed/neighbor/cell configuration of $4\sigma/2\sigma/0\sigma$. The results presented below are shown at the electromagnetic scale.

The 200 GeV energy distribution for a given impact position is fit to a double Gaussian. The mean is calculated and used as the mean energy response of the FCal at that impact point. The average radial distance from the beam line is calculated using the BPC tracks for each impact point projected onto the front face of FCal1. Figure 8 (left) shows the mean energetic response of 200 GeV electrons as a function of the mean impact point for positions 1, 2, 3, and 4H (representing increasing radial distance from the beam line). As expected, closer to the beam line there is a decreased response. A similar figure for 200 GeV hadron data is shown.
in Figure 8 (right). The energy loss down the beam line is more severe for hadrons, as their showers tend to be larger than electron showers and more energy is lost down the beam line. Ongoing studies will examine how the energy is clustered on the opposing side of the beam pipe where it is known that energy is splashed.

![Figure 8](image)

**Figure 8.** The mean reconstructed energy as a function of radial distance from the beam line for 200 GeV electrons (left) and hadrons (right). These four points represent data taken at impact positions 1, 2, 3, and 4H (with increasing radial distance from the beam pipe).

5. Summary
The performance of the ATLAS forward calorimeter has been studied using test beam data of electrons and hadrons at a range of energies from 10 to 200 GeV. Using a cylindrical clustering algorithm the intrinsic energy resolution of electrons is found to be \(28.5 \times \frac{\text{GeV}}{\sqrt{E}} \pm 3.48\%\). The electron data was used to confirm predictions of the electromagnetic scale for FCal1. The test beam hadron data were used to investigate a hadronic weighting scheme in the FCal, making use of the unique geometrical arrangement of the electrodes. Using the flat weighting technique the hadron energy resolution is found to be \(95.3 \times \frac{\text{GeV}}{\sqrt{E}} \pm 7.5\%\). The energy resolution is improved by using the radial weights. Both weighting techniques result in an energy resolution that exceeds the ATLAS design requirements of \(100 \times \frac{\text{GeV}}{\sqrt{E}} \pm 10\%\).

Further information about this test beam setup and data analysis of the 4L position electron and hadron data can be found in [4]. Work is ongoing to investigate alternative clustering algorithms used in ATLAS that have the ability to suppress electronic and pileup noise, which will be a valuable tool for the FCal in its high flux environment. Additional work is being carried out with the test beam data and Monte Carlo simulations to study the effect of the presence of the beam line, and energy losses down the beam line. These analyses will be the subject of future publications.

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