Performance of the ATLAS Forward Calorimeters in First LHC Data

Dag Gillberg, on behalf of the ATLAS Liquid Argon Calorimeter Group
Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada
E-mail: dag.gillberg@cern.ch

Abstract. The ATLAS Forward Calorimeters (FCal) cover the very forward region of $3.1 < |\eta| < 4.9$ and are hence designed to operate in a very high rate environment. This paper discusses the design of the FCal and presents studies of its performance in beam test data and LHC collision data. Measurements of the signal pulse shape, and the distribution of reconstructed cell energies are presented and compared with the expectation from simulations. A measurement of the location of the FCal is also performed in the data by studying the average deposited energy as a function of transverse distance to the beam axis.

1. The ATLAS Forward Calorimeters

The ATLAS detector is a multi-purpose detector built around one of the four collision points of the Large Hadron Collider (LHC)—the world’s highest energy collider. The ATLAS Liquid Argon (LAr) Calorimeter is one of the major subsystems of ATLAS. An overview of the LAr calorimeters is shown in Figure 1.

The ATLAS forward calorimeters (FCal) are situated inside the endcap cryostats together with the electromagnetic endcap calorimeter (EMEC) and the hadronic endcap calorimeter (HEC). The FCal covers the very forward regions of $3.1 < |\eta| < 4.9$, where the energies and density of particles are very high. The main two motivations for the FCal are to improve the reconstruction of missing transverse energy $E_T$ (important for many physics analyses, e.g. SUSY

![Figure 1. The ATLAS LAr calorimeters.](image1)

![Figure 2. Cut-away view of the ATLAS forward calorimeter. Particles from the interaction point first traverse the electromagnetic FCal1 module (Cu/LAr-calorimeter) and thereafter the two hadronic FCal modules (W/LAr-calorimeters).](image2)
searches) and the identification and measurement of forward jets (for instance the forward jets that are produced in vector boson fusion processes).

The FCAL consists of three layers. The layer closest to the interaction point, FCAL1, is a Cu/LAr calorimeter designed for electromagnetic calorimetry. FCAL2 and FCAL3, are hadronic W/LAr calorimeters. Behind FCAL3 is a passive layer of brass that absorbs hadronic shower remnants that punch through. Figure 2 shows a drawing of this arrangement.

Originally, the FCALs were planned to be placed outside the endcaps, 15 m away from the interaction point (IP). Further studies favoured the current placement inside the endcap cryostat (5 m from the IP) for several reasons: this provides a smooth transition from the other calorimeters that reduces energy losses and improves the reconstruction of jets, electrons and $E_T$. It also provides shielding for the muon system.

In order to adequately reconstruct jets and missing transverse energy, the FCAL design requirement for hadronic energy deposits was set to $\sigma_E/E = 1/\sqrt{E} + 0.1$, without significant non-Gaussian tails. The FCALs are also required to have a fast response: $\mathcal{O}(25$ ns), to minimize the impact from pile-up, and to be radiation hard to cope with the design luminosity of the LHC: $\mathcal{L} = 10^{34}$ cm$^{-2}$s$^{-1}$.

A novel technology was developed to meet the design requirements. Each FCAL module consists of an absorber matrix with cylindrical “electrodes” arranged parallel to the beam pipe, extending the full length of the module ($\sim 45$ cm). As illustrated in Figure 3, each electrode consist of a “rod” (anode) inside a “tube” (cathode) with a narrow, LAr-filled, annular gap between the two. The LAr gap is significantly narrower than the 2 mm gap of a conventional LAr calorimeter: 0.27 mm, 0.38 mm and 0.50 mm for FCAL1, 2 and 3 respectively. This provides a fast readout and avoids problems from ion buildup. The LAr gap between the rod and tube

![Figure 3](image-url)

**Figure 3.** Close-up views of an electrode in the FCAL1 module. FCAL electrodes consists of a rod (anode), a liquid argon filled gap and a tube (cathode). The distance between the rod and the tube are maintained by a insulating, helically wound PEEK fiber. Figure from [1].

![Figure 4](image-url)

**Figure 4.** Left: Front-face view of the electrode arrangement of a portion of FCAL1 close to the inner-edge. The Molire radius $R_M$, the distance $r$ to the beam, and the pseudorapidity $\eta$ at the front face are also shown. Right: Photo of the front-face of a hadronic FCAL3 module. The ends of the PEEK fibers can be seen between the rods and the tubes. Figures from [2].
is maintained by an insulating PEEK fiber that is wound around the rod.

A FCal readout cell consists of several neighbouring FCal electrodes read out together. Fewer electrodes are grouped close to the inner edge, which ensures an $\eta-\phi$ granularity of about $0.1 \times 0.1$ or better for most of the electromagnetic layer. The arrangement of electrodes is shown in Figure 4.

The choice of tungsten as absorber in the hadronic FCal2 and FCal3 modules limits the transverse hadronic shower spread, which is especially important for $\eta$ determination in the forward region since a fixed distance here covers a larger $\eta$ interval. This choice also provides a compact calorimeter that can be placed a bit deeper in the cryostat (see Fig. 1), which reduces neutron albedo back into the inner detector. FCal1 has a depth of $28X_0$, and all three FCal modules have a combined depth of $10X_0$.

![Figure 5](image.jpg)

**Figure 5.** Expected FCal pulse shapes derived from beam test data [2].

2. Signal Pulse Shape

Figure 5 shows the FCal pulse shapes for each module derived from beam test data [2]. They have slightly different shapes due to the different LAr gap sizes, but are very similar for the channels within the same module. The pulse shapes have been studied in-situ using cosmic, beam splash and collision data. Figure 6 show the measured pulse shape in beam splash data for a channel in FCal3 compared with the expected pulse shape. The pulse shapes observed in data agree very well with the derived shapes from beam test data.

The energy of a channel is proportional to the amplitude of the pulse. The amplitude and timing of the pulse is reconstructed using the optimal filtering (OF) technique [3]. There are

![Figure 6](image.jpg)

**Figure 6.** Pulse shape observed in 2009 beam splash data. The expected pulse shape derived from beam test data (see Figure 5) is shown as a solid blue line.
ongoing studies that try to find an optimal metric to determine the quality of the pulse, such that readout problems can be effectively identified.

3. Results from Beam Tests
The performance of the FCal was studied using beam tests in 2003. The purpose was to measure the response and the resolution, and to study the shower shape and energy losses near the inner edge. Beams of hadrons and electrons with fixed energies in the range 10-200 GeV were directed towards five different impact points on the FCal. The final C-side (negative z) FCal modules were used, with close-to-final electronics.

Figure 7 shows results from the electron beam tests. A good linearity was observed, and the intrinsic resolution was measured to $\sigma_E/E = 0.285/\sqrt{E/\text{GeV}} \pm 0.035$ [2], which exceeds the design requirement of $\sigma_E/E = 0.35/\sqrt{E/\text{GeV}} \pm 0.05$. Figure 8 shows the performance derived from hadron beam tests. When including the energy of cells in a cylinder with radius 8 cm around the impact point, the measured hadronic resolution is $\sigma_E/E = 0.95/\sqrt{E/\text{GeV}} \pm 0.075$ [2], which is slightly better than the design criterion (see Section 1). For the measured results quoted above, the contribution from electronic noise was subtracted in quadrature from each measured resolution value. This was done since the electronic noise was not constant over the full set of runs used. Studies using more sophisticated clustering [4] and hadronic calibration schemes using radial weights have also been performed, and significantly improve the energy resolution [5].

These results were obtained from beam test with minimal upstream material and hence measure the intrinsic response and resolution. Beam tests were also performed with upstream material that provide more ATLAS-like conditions. Studies have also been performed of shower-shape variables that can be used to distinguish electromagnetic showers from hadronic ones (which can be used for electron identification), and of the energy losses down the beam pipe and other effects close to the inner edge of the FCal.

Figure 7. Left: Reconstructed energy in FCal1 for 150 GeV electron beam data. Energy from hadron contamination can be seen at lower energies. Right: Linearity of the FCal response for various electron beam energies.

Figure 8. Left: Reconstructed energy from a 100 GeV hadron beam. Middle: Energy response at the EM scale versus beam energy for beam test data (black circles) and simulated beam test data (red squares). Right: Measured noise-subtracted resolution versus beam energy, for hadron beam tests data.
4. Cell Energy Distribution

Figure 9 shows the measured energy for all FCal cells in $\sqrt{s} = 900$ GeV $pp$ collision data recorded in late 2009, compared with the expected distribution from simulated non-diffractive minimum bias data. Reasonably good agreement is observed. Many other quantities such as jet energy, jet transverse width and fraction of energy deposited in the electromagnetic layer have been studied and also show quite good agreement with the expectations from simulations [6].

![Figure 9. Energy distribution for the cells in the FCal for $\sqrt{s} = 900$ GeV $pp$ collisions candidates (red squares) and randomly triggered data (hashed area). The predicted distribution from non-diffractive minimum bias simulation is shown in yellow.](image)

5. Position Measurement

Since the flux and energy of particles increase steeply with $\eta$, and since this flux is symmetric around the beam spot, the energy density profile of a calorimeter can be used to determine its position relative to the beam axis. The FCals are very suitable for such measurements due to their position in the forward region close to the beam axis, and can be used both to determine its own position, and also to perform measurements of the beam spot location, complementary to the measurements performed by the inner tracking detectors.

Studies have shown that the energy density $\rho_E$ measured in the FCals, can roughly be described by

$$\rho_E = k \cdot r^{-m},$$

where $r$ is the (transverse) distance to the beam spot, and $k$ and $m$ are constants obtained from a fit. The energy density for a channel can be calculated as $\rho_E = \frac{\sum E_i}{N_{\text{events}} \times N_{\text{electrodes}}}$, where the sum is over all $N_{\text{events}}$ events, and $N_{\text{electrodes}}$ is the number of electrodes of the channel. This quantity is proportional to the energy per unit area that hit the front face of a given FCal module, since each electrode has the same dimensions. Figure 10 shows a plot of the energy density for each cell in the electromagnetic layer of the C-side FCal measured in $\sqrt{s} = 7$ TeV collision data. One can see that the energy density increase at smaller transverse distances $r$.

Several methods that use the average cell energy to determine the position of the FCal have been tested. One of them plots the energy density for each channel against its $x$ and $y$ coordinates (as in Fig. 10), and then performs a two dimensional fit using Eq. 1, modified to introduce two new free parameters corresponding to the shift: $r = |(x, y)| \rightarrow |(x + \Delta x, y + \Delta y)|$. The vector $(\Delta x, \Delta y)$ obtained from this fit is then the measured shift of the FCal relative to the beam axis.
Figure 10. Average energy per event and electrode read out in the electromagnetic layer of the C-side (negative $z$) FCal in 7 TeV collision data. The 1006 readout cells each consist of 16 or 4 electrodes and are here enclosed with black lines. The upper half of this module sees more energy than the lower half, indicating that the FCal is located a bit low relative to the beam spot.

It should be noted that the simplified relation between energy and distance given in Eq. 1 only give a reasonable fit for limited ranges of $r$. For instance, the energy density is not a smooth function of $r$ close to $r = 210$ mm since there is more upstream material in this region due to the presence of a support structure. The method outlined above is therefore repeated several times for different segments of $r$, resulting in several measurements that later are combined. Channels with readout problems might bias the fit, and must be identified and removed.

The position of the FCal was measured in both 900 GeV and 7 TeV collision data using the method outlined above, and also using other methods. The measurements indicate that the geometrical axis of both A- (pos. $z$) and the C-side (neg. $z$) FCal lie about 2 mm below the centreline of ATLAS, with smaller measured shifts along the horizontal $x$-axis (+0.5 mm and +1.0 mm for the A- and C-sides respectively). The downward shift is consistent with the expected installed position of the FCal modules relative to the centreline of the endcap cryostats in combination with a possible sag in the support structure due to the weight of the FCals (12 tonnes per side).

Summary and Outlook
The ATLAS Forward Calorimeters use a novel design with tubular electrode readout and narrow LAr gaps in order to operate in the very high radiation environment of the forward region. The performance observed in beam tests meets the design requirements, and the pulse shapes in collision data agree very well with expectations. Distributions of cell energies and jet properties also agree quite well with the expectation from simulations. The position of the FCal has been measured in data.

References
[1] A. Artamonov et al. 2008, JINST 3 P02010
[2] J.P. Archambault et al. 2008, JINST 3 P02002
[3] W.E. Cleland and E.G. Stern, Nucl. Inst. Meth. A 338 (1994) 467.
[4] W. Lampl et al., ATL-LARG-PUB-2008-002 (2008).
[5] Louise Heelan, J. Phys.: Conf. Ser. 160 012058 (2009).
[6] The ATLAS Collaboration, ATLAS-CONF-2010-055 (2010).