Performance of the ATLAS Liquid Argon Endcap Calorimeter in Beam Tests

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Abstract. The pseudo-rapidity region $2.5 < |\eta| < 4.0$ in ATLAS is a particularly complex transition zone between the endcap and forward calorimeters. A set-up consisting of 1/4 respectively 1/8 of the full azimuthal acceptance of the ATLAS liquid argon endcap and forward calorimeters has been exposed to beams of electrons, pions and muons in the energy range $E \leq 200$ GeV at the CERN SPS. Data have been taken in the endcap and forward calorimeter regions as well as in the transition region. This beam test set-up corresponds very closely to the geometry and support structures in ATLAS. A detailed study of the performance in the endcap and forward calorimeter regions is described. The data are compared with MC simulations based on GEANT 4 models.

1. Introduction
This talk summarizes the main performance parameters of LAr Endcap calorimeters in a beam-test, which was carried out in 2004. It is a continuation of calibration studies of individual parts - electromagnetic (EMEC) [1, 2, 3, 4], hadronic endcap (HEC) [5, 6] and forward calorimeters (FCal) [7]. This beam-test cover particularly difficult forward region $2.5 < |\eta| < 4.0$ (the transition from the electromagnetic endcap calorimeter EMEC and hadronic endcap calorimeter HEC to the forward calorimeter FCal). The set-up was as close as possible to the final ATLAS detector, also with respect to the support structures and dead material distribution. It should be stressed that the set-up reproduced the ATLAS projective geometry at one $|\eta|$ point, but not over the entire $|\eta|$ region. The beam was incident at an angle of 4.2° onto the face of the calorimeters, corresponding to an average $|\eta|$ of 3.2.

2. Setup and Data
The beam tests have been carried out in the H6 beamline at the CERN SPS, which provides hadrons, electrons or muons in the energy range $6$ GeV $\leq E \leq 200$ GeV. The particle trigger was based on the coincidence of three scintillation counters S1, S2 and S3, and in order to be able
Figure 1. Schematic view of the general beam test set-up. Shown are the modules in the cryostat and the beam instrumentation used: multiwire proportional chambers (BPC), scintillation counters (S, B) and scintillator walls (V, M1, M2). The beam moves from right to left.

to adjust for the various vertical beam positions, these counters - as well as the beam chambers - were mounted on a vertically movable table. The impact position and angle of beam particles were derived using hit information from 6 multiwire proportional chambers (BPC-1 - BPC-6), each with a vertical ($y$) and horizontal ($x$) read-out plane. The positions of the BPC wire planes along the beamline were surveyed prior to the beam test. Track fits were performed separately in the $x - z$ and $y - z$ planes. Average track residuals calculated run-by-run for the full run period are typically below $\sim 200 \, \mu m$, in both coordinates. This tracking system allowed determination of the particle impact angle with a precision of $\sim 10 \, \mu rad$ and the impact point with a precision of $\sim 100 \, \mu m$ (at high energies).

The beam enters through the cryostat window from right at a nominal position of $y = 0 \, cm$. Shown are the inner EMEC (front), the HEC front wheel and rear wheel modules as well as the FCal1 and FCal2 modules (below the HEC modules) inside a cryostat. In addition a cold tail catcher is placed right behind the last FCal module in order to measure any leakage beyond the FCal2 module. In a similar way the energy leakage for the rear wheel HEC modules is measured in a warm tail-catcher (TC) placed outside the cryostat.

The electromagnetic endcap calorimeter (EMEC) is a liquid argon (LAr) sampling calorimeter with lead as absorber material. The liquid argon gap between the absorber plates increases with the radius and the accordion wave amplitude. For this beam test a module of the inner wheel has been rebuilt using leftover electrodes available. Except for the missing outermost electrode in azimuth ($\phi$), it corresponds exactly to a module from the series production.

The hadronic endcap calorimeter (HEC) \cite{5, 6} is a liquid argon sampling calorimeter with flat copper absorber plates, structured longitudinally in two separate wheels. Longitudinally each wheel has two read-out sections. Due to the limitation in space, a special set of 8 front and 8 rear HEC modules has been built for this beam test. These had a reduced coverage in $|\eta|$, corresponding to $2.1 < |\eta| < 3.2$. Also the rear modules were of half size in depth.

The forward calorimeters (FCal) \cite{8} cover in ATLAS the region $3.1 < |\eta| < 4.9$. Each endcap is made of three modules, one behind the other, providing three depth segments. All modules have cylindrical electrodes made of a solid rod within a thin-walled tube. The gap between the rod and the tube fills with liquid argon. The electrode rods, tubes, and matrix of the electromagnetic module are made of copper. The next two modules are hadronic calorimeters. Their electrode rods are solid tungsten, the tubes are copper, and the matrix is sintered tungsten alloy. The FCal modules used in this beam test are engineering prototypes of the FCal1 and FCal2 ATLAS modules and are those used in the 1998 beam tests \cite{7}.

In the two run periods more than 4000 runs have been taken with electrons, pions or muons in the energy range $6 \, GeV \leq E \leq 200 \, GeV$ with about 80 million triggers in total. Energy scans have been taken at a standard set of impact points. In addition, horizontal and vertical scans.
have been done at fixed particle energies. The frequently used impact points D and H for the
EMEC/HEC and FCal data correspond to $\eta = 2.8$ and $\eta = 3.65$ in ATLAS.

We focus in this talk on the electron and pion performance results in the EMEC/HEC and
FCal regions. First results from the vertical scan covering the full crack region are given as
well. Here it is only relevant to compare the data with MC simulation in order to verify the
geometry and inactive material distribution. Also a discussion of noise cut influence to a energy
reconstruction performance is added.

The noise subtraction for the data has been done using the exact list of read-out cells in
a data cluster for the next random trigger event in the same data file. Thus for the noise
estimate a close correlation to the real event with respect to time and actual cluster is kept.
Table 1 shows the typical noise, in MeV, at the appropriate electromagnetic scale, for cells in the
different longitudinal sections of the three calorimeter systems. Table 2 shows the corresponding
mean reconstructed noise, for a number of different cone sizes $R$. For the electromagnetic
sections of the EMEC and FCal, the noise is reconstructed at the electromagnetic scale, using
cone sizes appropriate for electromagnetic clusters. The right half of the Table 2 shows the
reconstructed noise expected for the reconstruction of pion data. These use the larger cone
sizes more appropriate to hadronic reconstruction and sum over all longitudinal sections. These
results, in GeV, have been calibrated to the hadronic energy scale.

Table 1. Example of typical mean cell noise (MeV) on the electromagnetic scale

| Calorimeter section | EM2 | EM3 | HEC0 | HEC1 | HEC2 | FCal1 | FCal2 |
|---------------------|-----|-----|------|------|------|-------|-------|
| Mean Noise [MeV]    | 80  | 60  | 200  | 280  | 460  | 240   | 370   |
| Expected Noise [MeV]| 80  | 60  | 190  | 250  | 420  | 180   | 315   |

Table 2. Example of mean noise (GeV) in typical cone for electrons ($R = 0.15$ and $R = 0.25$)
and hadrons ($R = 0.30$, $R = 0.40$ and $R = 0.50$). The energy is given on the electromagnetic
scale for electrons and on the hadronic scale for hadrons.

| Cone               | $R = 0.15$ | $R = 0.25$ | $R = 0.30$ | $R = 0.40$ | $R = 0.50$ |
|--------------------|------------|------------|------------|------------|------------|
| EMEC/HEC [GeV]     | 0.55       | 1.3        | 4.2        | 5.6        | 7.1        |
| FCal [GeV]         | 0.59       | 1.1        | 3.1        | 4.6        | 6.7        |

To compare data with MC expectation the simulation code GEANT 4 [9], version 7.1 has
been used. From the physics lists for hadronic shower simulations available in GEANT 4 the
physics lists QGSP-GN 2.6 and QGSP-BERTINI 2.6 have been used. The QGSP-BERTINI
option is expected to increase the shower size somewhat in comparison to the QGSP-GN version
and thus should give a better description of the shower shapes. Therefore both options have
been used for the study of the pion shower shape.

3. Electron and Pion Results

Figure 2 shows the response for electrons of 193 GeV when performing a vertical scan at $x = 0$
covering almost the full acceptance. A cone size of $R = 0.15$ has been used. Shown is the total
response as well as the response in the main longitudinal section of either the EMEC or FCal.
In all figures in this chapter the open symbols represents the MC, the solid one a data. The
small deviation of the data from MC prediction at $y \sim -115$ mm is due to a weak response of
a single electronic channel in the data.

Figure 3 shows the response as function of energy for electromagnetic clusters for the EMEC
impact point D (corresponding to $|\eta| = 2.8$, and for FCal impact point H. For the cone size of
Figure 2. Energy response for electrons of 193 GeV when performing a vertical scan covering almost the full acceptance. Shown is the total response as well as the response in the main longitudinal section of either the EMEC or FCal.

Figure 3. Energy dependence of the response to electrons with the impact point in EMEC (a) and FCal (b). Shown are the results for a cone size $R = 0.15$ and $R = 0.25$.

$R = 0.15$ the leakage out of cluster is $\sim 4\%$ at high energies in point D and $\sim 5\%$ in point H. The linearity is well described by the MC, the deviations at low energies are to a large extent due to the dead material in the beam in front of the active calorimeter, as expected from and seen in MC simulations.

Similarly the energy resolution has been studied for electrons reconstructed in a cone. The results are shown in figure 4 after noise subtraction and compared with MC expectations. The resolution has been parametrized using

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b.$$  \hspace{1cm} (1)

For the larger cone option the data yield typically a sampling term of $a = (13.5 \pm 0.5)\% \sqrt{\text{GeV}}$ and a constant term $b = (0.7 \pm 0.1)\%$ in point D and $a = (29.3 \pm 0.7)\% \sqrt{\text{GeV}}$ and a constant term $b = (3.0 \pm 0.1)\%$. in point H. In general, the energy resolution expected from MC is somewhat better than seen in the data. This holds for both cone sizes, particularly at low energies. For the larger cone option the MC prediction is approaching the data at higher energies. But for the smaller cone option the data yield a somewhat larger constant term.

As was the case for electrons, a vertical scan of the response to pions can reveal the fine structure of the hadronic calorimeters of the set-up. Figure 5 show the response on the
Energy dependence of the energy resolution for electrons with the impact point in EMEC (a) and FCal (b). Shown are the results for a cone size of \( R = 0.15 \) and \( R = 0.25 \).

Electromagnetic scale for pions of 200 GeV. In general, the MC predicts a larger signal in the electromagnetic sections and a smaller one in the hadronic sections compared to the data. This is a well known problem in the GEANT 4 QGSP and QGSP-GN simulations, yielding somewhat more compact hadronic showers than seen in the data. Except for this overall scale factor, the MC shows a rather good agreement with the data, in particular for the details of the response when passing the crack region.

Figure 5. Energy response on the electromagnetic scale for pions of 200 GeV when performing a vertical scan. Shown is the response in the FCal1, total EMEC, as well as in the two main longitudinal sections of the EMEC on part (a), and FCal2, total HEC, as well as in the individual longitudinal sections of the HEC (HEC1, HEC2, HEC3) on part (b). For the energy reconstruction a cone size of \( R = 0.30 \) has been used.

The response as function of energy has been studied for pions using energy deposits on electromagnetic scale within a cone of \( R = 0.3 \) and \( R = 0.5 \). Figure 6 shows the response as function of energy. The expectations from MC simulations are shown as well. The data for the smaller cone size are somewhat below the MC expectations. Part of the difference might be the rather compact lateral shower size in GEANT 4 QGSP with respect to the data, an effect which seems to be more pronounced at low energies (see e.g. [10]). For the larger cone size the MC describes the data reasonably well.
The energy resolution for pions is affected by the different and in addition energy dependent response to pions in the different calorimeter sections. Therefore we tried to compare the data with MC simulations using the ‘bench mark approach’, where one calibration constant per longitudinal section and energy is used, rather than one overall calibration constant at each energy as done in the HEC stand alone beam tests (for details see [5]). Figure 7 shows the energy resolution as function of energy. The expectations from MC simulations are shown as well. The noise has been subtracted. The energy resolution expected from the MC simulation

\[(a) \quad (b)\]

Figure 6. Energy dependence of the response to pions with the impact point in EMEC (a) and FCal (b), using the electromagnetic scale. The energy has been reconstructed within a cone of \(R = 0.3\) and \(R = 0.5\) respectively.

\[(a) \quad (b)\]

Figure 7. Energy dependence of the energy resolution for pions with the impact point in EMEC (a) and FCal (b), using the bench mark approach. Here one calibration constant per longitudinal section has been determined from a fit minimizing the energy resolution. The energy has been reconstructed within a cone of \(R = 0.3\) resp. \(R = 0.5\).

(GEANT 4 QGSP-BERTINI) is in rather good agreement for the higher energies and for the larger cone, but at low energies is somewhat better than what is seen in the data. The resolution has been parametrized using equation (1). For point D the data for the cone size \(R = 0.5\) yield typically a sampling term of \(a = (88 \pm 5)\%\sqrt{\text{GeV}}\) and a constant term \(b = (6.8 \pm 0.4)\%\) whereas the MC expectations are \(a = (72 \pm 1)\%\sqrt{\text{GeV}}\) and \(b = (7.5 \pm 0.1)\%\) respectively. The differences in the terms obtained are largely driven by the somewhat different energy dependence, yielding a better resolution for the MC at low energies, but being in agreement with the data at high.
energies. The conclusions are similar for point H, where data yield typically a sampling term of $a = (98.5 \pm 4.0) \% \sqrt{\text{GeV}}$ and a constant term $b = (6.4 \pm 0.4) \%$ whereas the MC expectations give $a = (74.9 \pm 1.2) \% \sqrt{\text{GeV}}$ and a constant term $b = (7.7 \pm 0.1) \%$.

The lateral shower shape has been studied using a horizontal scan with pions at 60 GeV (see Fig. 8). Shown is the energy in individual $\phi$ wedges of $\Delta \phi = 0.2$, integrated in $\eta$ and summed for the EMEC and HEC calorimeters. At each pion impact point the eight contributing signals using the electromagnetic scale have been studied, two of them are rather small. The six most relevant signals are shown for the data and MC prediction using GEANT 4 with the QGSP-BERTINI physics list. In general the MC prediction describes the data well.

4. Noise Cuts Analysis

Because of usage of topological clustering as a default in ATLAS reconstruction, we have also tried to check the influence of various noise cut on response and resolution. In the figure 9(a), the response of the electrons with cone cluster of $R = 0.25$ is shown, only cells passing the noise cut are taken into energy sum. The cut $-3\sigma$ means no cut at all, and cut is asymmetric, only positive signals are taken into account. In figure 9(b) the resolution dependence of the same cluster is shown. Similar plots for pions are shown in figure 10. We see, that the optimal cut in the case of electrons is a $3\sigma$, whereas for pions $0\sigma$ brings the best performance.

Figure 8. Lateral shower shape for pions at 60 GeV. Shown is the energy in individual $\phi$ wedges of $\Delta \phi = 0.2$, integrated in $\eta$ and summed for the EMEC and HEC calorimeters. At each pion impact point the six relevant contributing signals using the electromagnetic scale are shown.

Figure 9. Response (a) and resolution (b) dependence on $\sigma$ cut used on cells in cone $R = 0.25$ for electrons in point D.
Figure 10. Response (a) and resolution (b) dependence on $\sigma$ cut used on cells in cone $R = 0.25$ for pions in point D.

5. Conclusions
The region of the ATLAS endcap (EMEC/HEC) and forward (FCal) calorimeters in the pseudorapidity range $2.5 < |\eta| < 4.0$ has been studied in beam test runs with electrons and pions. The performance of the EMEC/HEC as well FCal for electrons and pions has been assessed. The results have been compared in detail with MC simulations (GEANT 4). In general, the data show agreement with MC predictions at higher energies. At low energies the GEANT 4 physics list QGSP-GN predicts a somewhat larger pion response (at the electromagnetic scale), coupled with a better energy resolution and more compact shower size than seen in the data. Here QGSP-BERTINI yields a better agreement, in particular for the shower shape.

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