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Commissioning and Performance of the ATLAS Liquid Argon Calorimeters

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The ATLAS liquid argon (LAr) calorimeter system consists of an electromagnetic barrel calorimeter and two end-caps with electromagnetic, hadronic and forward calorimeters. The construction of the full calorimeter system is completed since mid-2004. The detector has been operated with LAr at nominal high voltage and fully equipped with readout electronics. Online software, monitoring tools and offline signal reconstruction have been developed for data collection and processing. Extensive tests with calibration pulses have been carried out, and the electronics calibration scheme for all 182468 channels has been exercised. Since Augst 2006, cosmic muon data have been collected together with the rest of the ATLAS detector system as part of the ATLAS commissioning program. The reconstructed LAr signals from energy deposited by cosmic rays are compared to the prediction derived from measured detector parameters and calibration pulses. The uniformity of the detector response within regions that have sufficient cosmic muons are examined. The expected performance of the LAr calorimeter for ATLAS physics, based on previous beam tests and Monte Carlo simulation, is also summarised.

1. THE ATLAS LIQUID ARGON CALORIMETERS

ATLAS [1, 2] is a general-purpose detector built for operation at the Large Hadron Collider (LHC) at CERN. The LHC is a proton-proton collider which will operate with a center-of-mass energy of 14TeV. A system of LAr calorimeters located in three separate cryostats between the inner tracking detectors and the outer muon chambers forms one of the major ATLAS detector systems [3].

1.1. Physics Requirements

The requirements for EM calorimetry in ATLAS are driven by the discovery potential of the LHC [4]. Major goals in the design of the LAr calorimeters have been sensitivity to the electromagnetic Higgs decay channels H$\rightarrow\gamma\gamma$ and H$\rightarrow$ee as well as the ability to detect an electromagnetically decaying exotic heavy resonance like a hypothetical new neutral gauge boson (Z$'$) or an excited graviton (G^*). Furthermore, the EM calorimeters are required to ensure sensitivity to a wide range of supersymmetric scenarios.

Full coverage in azimuthal angle ϕ and EM coverage up to pseudorapidities of $|\eta| < 3.2$ ($|\eta| < 2.5$ with high precision) without insensitive regions is achieved through an accordion geometry. Good energy resolution with a stochastic term of $< 10\%/\sqrt{\mathrm{GeV}}$, a noise term of $<$ 300MeV and a constant term of $<$ 0.7% requires precise mechanics and electronics calibration. Precision measurements like the determination of the mass of the W boson ask for a linearity of better than 0.1%, which requires a very good understanding and correction of dead material effects. Particle identification (separation of electrons from jets and photons from single π_0) is crucial for many physics signatures and requires a lateral and longitudinal segmentation and a fine granularity in the first sampling layer. A rejection of single π_0 of better than 3 for transverse momenta above 50 GeV is achieved with an angular resolution of better than 50 mrad/$\sqrt{\mathrm{E}}$. The ability to detect electromagnetically decaying heavy resonances at the kinematic limit sets the dynamic range from about 30 MeV up to 3 TeV, corresponding to an effective readout resolution of about 17 bits. To minimise pile-up effects from overlay events at the LHC collision rate of 40 MHz and at the LHC design luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a fast response of the readout is necessary, which is achieved by using small readout gaps and bipolar shaping. The LAr calorimeters are also expected to contribute to the measurement of hadronic and missing energy in the forward region. For this purpose, hadronic and forward calorimeter systems

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have been implemented, extending the coverage up to $|\eta| < 4.9$ with an energy resolution of $\sigma_E/E \approx 50\%/\sqrt{\mathrm{E}} \oplus 3\%$ for $|\eta| < 3$ and $\sigma_E/E \approx 100\%/\sqrt{\mathrm{E}} \oplus 10\%$ for $|\eta| > 3$.

1.2. Electromagnetic Calorimeters

A Pb/LAr sampling technique with an accordion geometry was chosen both for the electromagnetic barrel calorimeter (EMB) and for the electromagnetic endcap calorimeter (EMEC). Using LAr as the active medium results in inherent linearity, radiation hardness and a fast buildup of the ionisation signal. Cu edging of the readout electrodes allows for a small gap width of $\approx 1-3$ mm, leading to a drift time of approximately 450 ns. A nominal high voltage of 1 kV/mm is applied, with a two-fold redundancy per readout electrode. A total of 173312 readout channels is distributed over 4 longitudinal layers covering the region up to $|\eta| < 1.475$ (EMB) and $1.375 < |\eta| < 3.2$ (EMEC). A presampler (for $|\eta| < 1.8$) measures the energy loss in the material in front of the active calorimeters and inside the cryostats, which corresponds to approximately 2-6 radiation lengths X_0. It is followed by the finely segmented strips layer used for discrimination between photons and single π_0 (granularity from $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$ to 0.1×0.1 and depth of $\approx 4X_0$). The middle layer contains the bulk of the EM shower energy ($17 - 20X_0$). The back layer contains the remaining part of the EM shower ($2 - 10X_0$) and is used for rejection of hadronic showers.

1.3. Hadronic Endcap Calorimeter

A Cu-Ar sampling technique is used for the hadronic endcap calorimeter (HEC), which consists of two wheels (HEC1 and HEC2) in each endcap cryostat and covers the range $1.5 < |\eta| < 3.2$. Double gaps on either side of the Cu readout electrode with a total width of approximately 8.5 mm lead to a sampling fraction of 4.4% (HEC1) and 2.2% (HEC2). Low noise GaAs preamplifiers mounted inside the cryostats are used to readout the signals of the 5632 channels. The granularity in $\Delta\eta \times \Delta\phi$ is $0.1 \times 0.1/64$ (for $|\eta| < 2.5$) and 0.1×0.2 (for $2.5 < |\eta| < 3.2$).

1.4. Forward Calorimeter

The forward calorimeter (FCal) is composed of three modules featuring cylindrical electrodes (rods) with thin liquid argon gaps. An electromagnetic module with Cu absorber is followed by two hadronic modules with tungsten absorbers, covering the range from $3.1 < |\eta| < 4.9$ with 3524 readout channels. The charges are collected on thin tubes maintained between the absorber matrix and the rods, which allow to reduce the gap widths to approximately 0.25 mm to 0.5 mm and therefore reduce the effect of ion buildup in this high-flux region.

1.5. Detector Readout and Calibration

Both the frontend-readout and the electronics calibration systems are mounted on detector and must therefore be able to tolerate significant levels of radiation. The on-detector location also implies that access to the frontend electronics is limited to the long shutdown periods foreseen in yearly intervals and therefore reliability of the readout and calibration system is a key concern. This holds in particular for the first stage of amplification of the HEC readout signals, which is performed by GaAs preamplifiers mounted in an inaccessible position inside the cryostats.

Frontend boards are used for preamplification, bipolar shaping in 3 separate gain scales and analog storage of the detector signals during the level-1 trigger latency of ≈ 2.5 μs [5]. The analog signals are digitised at the LHC bunch-crossing frequency of 40 MHz on the frontend boards and sent off-detector to the readout drivers through optical links. During LHC running 5 time samples of 25 ns are readout for each event. For commissioning studies up to 32 samples can be readout. The frontend boards also provide the first stage of summation of the analog signals used for the level-1 trigger.

The readout drivers calculate energy, time and a χ^2-like quantity characterising the quality of the waveform [6]. Furthermore, they provide energy-weighted position moments for the missing transverse energy calculation performed by the higher-lever trigger as well as monitoring histograms.

An electronics calibration system is used to characterise and monitor the response of the detector cells [7]. Charges are injected very close to the electrodes, resulting in a signal shape close to the ionisation signal. For the FCal a simpler calibration scheme was chosen, where the calibration signals are injected directly into the frontend-readout boards. The dynamic range of the calibration system is 16 bits and the observed non-linearity is less than 0.1%. Optimal filtering coefficients are obtained from the calibration data taken in between LHC fills, which are used during physics running to calculate the energy online in the readout drivers.

1.6. Commissioning with Calibration Measurements

The construction and installation of the liquid argon calorimeter and its readout system has been completed in March 2006. The calibration and readout system have been used extensively during all stages of installation and commissioning, to support the debugging and repair of hardware problems. Monitoring of the readout status continues after loss of access to the frontend electronic with the closure of the detector in June 2008. The current situation is satisfactory:

Dead readout channels: Only 0.02% of all channels inside the detector are found to show no readout signal. No continuous dead regions are observed. For about 0.9% of all channels the frontend readout is currently not functioning. These recent problems are expected to be fixed in the shutdown following the first beam commissioning period of the LHC machine.

Problematic channels: About 0.5% of all channels show minor problems like increased noise or damaged calibration lines. Offline corrections are applied in these cases and the impact on the calorimeter performance is negligible. No continuous problematic regions are observed.

High-voltage status: Less than 1% of all HV channels are operated at reduced voltage. The voltage is sufficient to guarantee usable signals for all readout electrodes.

2. COSMIC DATA TAKING

Cosmic muon signals are the first and only physics data before LHC operation starts. The LAr calorimeters take cosmic runs since 2006, with a few 10^7 events analysed so far. Dedicated cosmics triggers based on the hadronic tile calorimeter ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$) and more recently other triggers (e.g. the level-1 calorimeter trigger) have been used. Two different selections are applied for the offline analysis of the data: 1) Samples of high-energy muons with reconstructed cluster energies above 500 MeV are used to check the quality of the physics-pulse prediction. The limited acceptance and statistics of this selection ($\approx$1% of the total cosmics yield) allow only for qualitative studies. 2) Minimum ionising particles (MIPs) are selected to check the EM performance in terms of uniformity and timing. The observed signals are mostly small and non-projective.

2.1. Quality of Physics-Pulse Prediction

High-energy muons (E$>$ 500 MeV) are selected and the observed physics pulses are compared to the prediction from a factorisation of the calibration-readout response (Fig. 1a). Good agreement and a coherent quality of the signal-reconstruction is observed for the 5 highest samples over the whole range of the EM calorimeters ($|\eta| < 3.2$). Small deviations of the observed signals from the prediction for the later samples of the pulse are understood to be caused by variations in drift time due to displacements of the readout electrodes between the absorbers from their nominal positions. The good understanding of the readout response leads to very small systematic effects from the signal reconstruction.

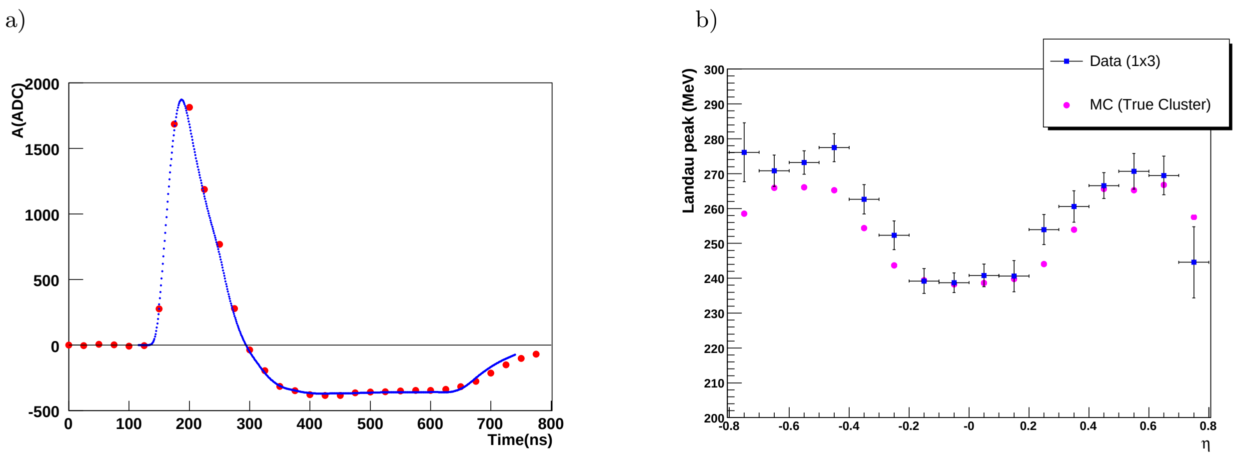

Figure 1: a) Observed physics pulse (dots) and prediction from factorisation of the calibration readout response (solid line). b) Response non-uniformity for a selection of cosmic muon events as function of pseudorapidity. The data (dots with error bars) are compared to the prediction from a MC simulation (dots).

2.2. Uniformity Studies with MIPs

A more inclusive selection of projective MIPs in the region $|\eta| < 0.8$ was used to study the uniformity of the calorimeter response [8]. A 1x3 cells clustering algorithm was used for the reconstruction of the calorimeter energy and compared to a Monte Carlo (MC) simulation. A landau distribution of the reconstructed energy was observed and the agreement between data and MC for the response non-uniformity was found to be within 3% over the whole η range (Fig. 1b).

3. PERFORMANCE IN TESTBEAM

The expected performance of the EM calorimeter is estimated from results of a combined testbeam in 2004. A full slice of the barrel detector was placed in a magnetic field of 1.4 T and subject to particle beams of electrons, photons, pions, protons and muons from 1 to 350 GeV. The results have been used to validate the calorimeter simulation and to extract performance parameters like resolution, linearity and uniformity.

The ATLAS calibration strategy foresees to extract the calibration parameters from a MC simulation. The energy calibration of the LAr calorimeter therefore relies on precise MC simulations of the calorimeter response. The reconstructed cluster energy for the different layers of the EM calorimeter has been studied for electrons from 1 to 250 GeV and for different amounts of dead material in front of the calorimeter. Good agreement with the simulation within 0.4% was obtained (Fig. 2a). The level of agreement is limited by the systematic uncertainty of the beam energy measurement and the simulation of the beamline setup.

The energy linearity of the calorimeter response has been studied for electron-beam energies between 1 and 250 GeV and for 4 different configurations of dead material in front of the calorimeter. The observed non-linearity is of the order of 0.5% (Fig. 2b). The main cause for the observed non-linearity is the description of the setup by the simulation. For a previous standalone testbeam, where the simulation of the beamline setup was controlled to very high precision, a non-linearity of 0.1% was found [9], in agreement with the specification. The non-uniformity after applying cell-level and cluster-level corrections was estimated for electron beams up to 245 GeV to be approximately 0.5% [10].

The energy resolution has been studied for different configurations of dead material in front of the calorimeter. It was found that the resolution worsens at a rate of approximately $0.5\%/\sqrt{\mathrm{E}}$ per 30% increase of a radiation length, X_0. Good agreement between data and MC simulation was observed.

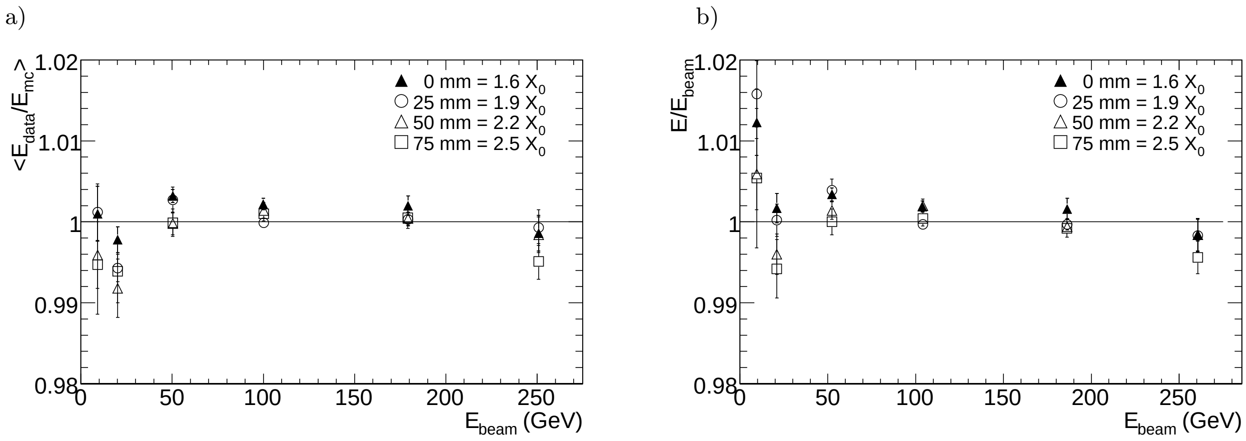

Figure 2: a) Ratio of reconstructed over simulated electron cluster energy as function of beam energy, for 4 configurations of dead material. b) Ratio of reconstructed electron energy after calibration over beam energy for 4 configurations of dead material.

4. CONCLUSIONS

The installation of the LAr calorimeters has been completed and the apparatus is now closed. Calibration measurements and cosmic muon data are used successfully and continuously to commission and monitor the LAr detector and its readout. Preliminary studies show only a small number of isolated permanently dead readout channels of 0.02%. All high voltage channels are operating, less than 1% of them at reduced voltage but with still usable signals. Analysis from a combined test beam shows encouraging performance results. Good agreement between data and MC simulation is observed. Linearity, uniformity and resolution are in agreement with expectations.

5. ACKNOWLEDGMENTS

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