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Precision linearity studies of the ATLAS liquid Argon EM calorimeter

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**Motivations and Method**

Electromagnetic Calorimetry for the general-purpose ATLAS experiment at the LHC should provide a linearity well within 1 % from the GeV to the TeV scale and even much better in limited energy ranges

e.g. precision measurement of W mass requires a linearity within a few $10^{-4}$ between 30 and 80 GeV

First precision linearity measurement has been performed on a LAr Barrel Calorimeter module, exposed to electron beam (CERN H8 test line)

Need to know the beam energy scale to a few $10^{-4}$

(calibration of the beam line between 10 and 180 GeV)

Need to understand in principle the most suitable energy reconstruction procedure

(study detector response through accurate MC (Geant4) simulation)

Need to accurately inter-calibrate the detector layers

(understand effects on linearity of calibration, noise...)

Beam Energy Measurement

\[ E_{\text{beam}} \propto \int Bdl \]

Energy range:
10 to 180 GeV

Need precise bending power calibration of a magnet triplets (B3 in the sketch, B4 off and degaussed), as a function of the current pulsed in the magnets.

The current is measured with \(10^{-4}\) accuracy using DCCT.

Calibration performed by CERN SL team on a reference magnet by measuring the voltage induced by current pulsing on a narrow loop made of two wires stretched along the beam path.

Accuracy: better than \(10^{-4}\) on the range of interest.

Cross-check: all along the data taking, the field in one of the B3 magnets was monitored using two Hall probes located just outside the beam pipe, in order to check the reliability of the current measurement.

The Hall probes were also calibrated on the reference magnet.
The magnets in the test beam line and the calibration one are part of a set of 100 SPS magnets, tuned to be identical at $\pm 2 \times 10^{-4}$ in 1977. Some residual differences between calibration and beam magnets have been corrected...

Detailed calibration curves can be compared with analogous measurements performed in 1977 on another reference magnet. New measurements confirm 1977 calibrations.
Cross–check with Hall probes
check of absolute value of field vs current limited by differences among magnets in the border region (some discrepancies observed at the $1 \times 10^{-3}$ level).

However, stability with time of measured field for a given current value within probe accuracy (few $10^{-4}$)
$\implies$ accuracy of current measurement validated

Systematics
The dominant effect is the residual field in the degaussed magnets, inducing an offset on energy scale of $\pm 11$ MeV

$\implies \pm 1 \times 10^{-3}$ on linearity for $E > 10$ GeV

Uncorrelated errors on single points (dominated by uncertainty on differences among magnets) can affect the linearity only up to $\pm 3 \times 10^{-4}$

<table>
<thead>
<tr>
<th>current (A)</th>
<th>$\int B dl$ (Tm)</th>
<th>electron mean energy (GeV)</th>
<th>error (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.315</td>
<td>1.3664</td>
<td>10.0820</td>
<td>0.0132</td>
</tr>
<tr>
<td>93.133</td>
<td>2.0379</td>
<td>15.0368</td>
<td>0.0088</td>
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<tr>
<td>124.363</td>
<td>2.7184</td>
<td>20.0579</td>
<td>0.0095</td>
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<td>155.513</td>
<td>3.3980</td>
<td>25.0714</td>
<td>0.0108</td>
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<td>186.689</td>
<td>4.0789</td>
<td>30.0954</td>
<td>0.0117</td>
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<td>217.900</td>
<td>4.7607</td>
<td>35.1258</td>
<td>0.0129</td>
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<td>248.973</td>
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<td>311.270</td>
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<td>373.484</td>
<td>8.1596</td>
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<td>559.524</td>
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<td>621.128</td>
<td>13.5634</td>
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<td>744.113</td>
<td>16.2383</td>
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<td>0.0368</td>
</tr>
<tr>
<td>926.708</td>
<td>20.1866</td>
<td>148.5927</td>
<td>0.0461</td>
</tr>
<tr>
<td>1115.230</td>
<td>24.1095</td>
<td>177.1730</td>
<td>0.0561</td>
</tr>
</tbody>
</table>
Effect of Bremsstrahlung

- Some material (vacuum windows, scintillation and Cerenkov counters, etc.) is spread along the \( \sim 170 \) m long beam line. Bremsstrahlung photons emitted far from the detector can be lost

\[ \implies \text{expect a tail in the beam energy distribution} \]

- Not easy to predict the equivalent amount of material producing the effect, expect between 0.06 and 0.1 \( X_0 \)

- but we can fit the reconstructed energy distributions (after a tight cut against pion contamination): tails are well reproduced at all energies with a MC simulation including Brem. losses in 0.08 \( X_0 \)

- tails, convoluted with the resolution, produce a bias on the peak between 0.45\% (10 GeV) and 0.12\% (180 GeV) that has to be corrected

Reconstructed energy

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CALOR 2004
The ATLAS LAr Barrel Calorimeter

(see talks by C. de la Taille, L. Serin, O. Gaumer)

- Pb/LAr sampling calorimeter with accordion geometry
- 4 longitudinal samplings with different transverse segmentation:
  Presampler (PS)
  + three accordion layers:
  STRIPS, MIDDLE, BACK

\[ \eta = h = h = h = 2 \]

\[ \theta = 0.687 \quad 1.475 \]

energy scan at this position

G. Graziani – Linearity of ATLAS LAr EMC
CALOR 2004
Energy must be reconstructed from the 4 samplings

\[ E = \sum_{i=1}^{4} w_i E_i \]

to preserve linearity, weights should be the inverse of the sampling fraction \( f_s \)

\[ w_i = \frac{1}{f_s} = \frac{E_{active}^e + E_{passive}^e}{E_{active}^e} \]

than can in principle depend on energy and can be obtained from MC:

- Full e.-m. shower Geant4 simulation, cutoff 30 or 15 \( \mu \)m
- Detector geometry in testbeam setup described in detail
- sampling fraction for electrons depends strongly on depth (Lead/Ar calorimeter!)
- accordion detector is designed carefully to have a depth-independent \( f_s \) for mips

G. Graziani – Linearity of ATLAS LAr EMC

CALOR 2004
Thus, sampling fraction scales with the longitudinal shower development.

For showers fully contained in the accordion detector, the sampling fraction becomes independent on energy and on longitudinal fluctuations.

⇒ need accurate intercalibration of the three accordion layers.
However, some energy of the shower is lost before (passive material, PS) and after the accordion (long. leakage) \(\rightarrow\) residual dependence of accordion sampling fraction on event depth \(D\) (estimated from longitudinal shower barycenter)

... but practically energy independent!!
Presampler calibration

- The energy lost upstream the accordion is estimated event by event by the Presampler.
- One can find empirically a “magic” weight that makes the full detector linear, and makes the reconstructed energy independent on long fluctuations at the same time:

\[ E \propto (5.6 \, E_{PS} + E_{ACCORD}) \]

- Unfortunately, this weight enhances sampling fluctuations in the PS  
  \[ \Longrightarrow \text{resolution is degraded} \]
Alternative: reconstruct energy as

\[ E = \frac{E_{PS}}{f_{e,PS}^e} + \frac{E_{ACCORD}}{f_{e,ACCORD}^e} + F_{\text{leakage}} \]

→ preserves the linearity by definition and gives much better resolution

Reconstruction becomes specific for electrons

\[ f_{e,ACCORD}^e \] and long. leakage fraction \( F_{\text{leakage}} \) can be parametrized only as a function of the event depth \( D \) and \( \eta \)

Resolution performances depend critically on how \( f_{e,PS}^e \) is parametrized and how the passive material between PS and STRIPS (\( \sim 0.2 \times X_0 \)) is taken into account;

Present approach:

Share the material between \( f_{e,PS}^e \) and \( f_{e,ACCORD}^e \) and parametrize both as a function of \( D, E \) and \( \eta \)

Under development (to improve resolution):

Upstream energy better described by \( a + bE_{PS} \)

Apply ad-hoc correction for the passive material \( (\propto \sqrt{E_{PS}E_{\text{STRIPS}}}) \)
DATA / MC comparison
(MC includes uncoherent noise)

Energy=30 GeV

Energy=90 GeV

Longitudinal Profile

Raw rec. Energy vs Event Depth

\[ \frac{E_{PS}}{f_s,PS} + \frac{E_{ACCORD}}{f_s,ACCORD} \]

Final rec. Energy vs Event Depth

\[ \frac{E_{PS}}{f_s,PS(D)} + \frac{E_{ACCORD}}{f_s,ACCORD(D)} \]

G. Graziani  Linearity of ATLAS LAr EMC

CALOR 2004
Test Beam Results

- Data taken during August 2002 at CERN H8 beam test line
- 16 energy points between 10 and 180 GeV
- only one position (beam time is limited!)

- energy reconstructed applying the weights obtained from MC simulation
- some other effects that may affect linearity, not accounted by the simulation, need to be considered:
  - cell’s electronic calibrations
  - cross-talk and noise
  - beam shape (geometrical corrections)
  - pion contamination
**Readout non-linearity**

- ADC dynamic range is covered by three gains (low, medium, high) differential non-linearities up to 0.5 % observed in electronic calibration for medium gain

- after refining calibration procedure, the energy measured with the two gains in the gain switch region ($E_{\text{cell}}^{\text{MIDDLE}} \sim 20 \text{ GeV}$) agree typically within $1 \times 10^{-3}$
Pion Contamination

- most of pions in the beam vetoed by counter downstream the detector
- transverse profile analysis: parametrize e.–m. shower profile with real electrons, and apply a $\chi^2$ cut:

$$\chi^2 = \frac{1}{N-3} \sum_{cells}^{layer=1,3} \frac{(E_i/E_{layer} - f_i(\Delta\eta, \Delta\phi))^2}{\sigma^2_{f_i}(\Delta\eta, \Delta\phi)}$$

where $E_i/E_{layer}$ is the fraction of layer energy in cell $i$

$\implies$ cut only depends on shower shape, not on absolute energies
- clear suppression of pions when looking at the total energy and PS energy
Layer Intercalibration

- guaranteed in principle by electronic calibration
- but cross-talk effects are different in each layer, due to different transverse segmentation
- in particular, a \( \sim 10 \% \) cross-talk among neighbour strips (at signal peak) needs to be corrected
- not easy to predict the effect after signal reconstruction based on optimal filtering, present estimate \( 6.5 \pm 1 \% \)

Systematic summary

**Correlated errors:**

- Strips cross-talk
- Uncertainty on MC weights
  - (estimated by comparing weights obtained with different MC productions, after varying the amount of passive material within uncertainty)
- Beam energy offset

<table>
<thead>
<tr>
<th>Error on linearity for ( E &gt; 10 ) GeV</th>
<th>( \pm 0.2 % )</th>
<th>( \pm 0.15 % )</th>
<th>( \pm 0.1 % )</th>
</tr>
</thead>
</table>

**Uncorrelated errors:**

- geometrical corrections
- residual pion contamination

| Error on each point | \( \pm 0.05 \% \) | \( \pm 0.05 \% \) |
**Results**

(preliminary)

**Linearity**
(normalized to 100 GeV)

![Linearity Graph]

- Systematic error on linearity
- Uncorrelated syst. error on measurements

**Resolution**

- Real Data
- MC

![Resolution Graph]

**Beam Energy (GeV)**

**Linearity (Erec/Ebeam)**

**Resolution**

**Beam Energy (GeV)**
Conclusions

- first precision linearity study of ATLAS LAr Barrel Calorimeter
- single position scanned in the range 10 to 180 GeV
- detector was proved to be
  - linear within ± 0.25 % for E > 10 GeV
  - and within ± 0.1 % for E ≥ 40 GeV
- many effects investigated for the first time at this level of accuracy, still space for improvements for:
  - energy reconstruction
  - impact of cross-talk, noise, signal reconstruction on linearity
- new data will be collected during combined test-beam in 2004