LAL 98-102
December 1998

Laboratoire de l'Accélérateur Linéaire

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*Talk given at the 6th International Conference on Advanced Technology and Particle Physics
Villa Olmo, Como, 5-9 October 1998*

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Overview of the ATLAS electromagnetic calorimeter

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To satisfy the very tight physics requirements for an electromagnetic calorimeter at the LHC, the ATLAS collaboration has chosen a lead-liquid argon sampling technique, with the absorbers bent in accordion shape. The calorimeter concept will be presented here together with a discussion of the first full-scale module construction, with particular emphasis on mechanical issues.

1. Physics requirements

The main goal of the LHC is the discovery of the Higgs boson.

The Higgs production cross section in pp collisions is a rising function of the centre-of-mass energy and is very small; therefore for the LHC a high centre-of-mass energy, $E_{c.m.} = 14 \text{ TeV}$, and a high luminosity, $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, have been chosen.

The main experimental problem for Higgs detection at the LHC is that background cross sections are huge.

For the benchmark channel $H \rightarrow \gamma\gamma$, the most promising for Higgs boson search in the mass range $100 \text{ GeV} < M_H < 140 \text{ GeV}$:

- $\sigma(H \rightarrow \gamma\gamma) \sim 50 \text{ fb}$
- $\sigma(\gamma\gamma)_{QCD} \sim 10 - 100 \times \sigma(H \rightarrow \gamma\gamma)$
- $\sigma(\gamma\text{-jet}, \text{jet-jet})_{QCD} \sim 10^6 \times \sigma(H \rightarrow \gamma\gamma)$
- $\sigma(\text{total}) \sim 10^{12} \times \sigma(H \rightarrow \gamma\gamma)$

Therefore extremely demanding requirements are set on e.m. calorimetry performance in terms of

- **energy resolution**

In the range 10-300 GeV a sampling term of $\sim 10\%/\sqrt{E(\text{GeV})}$, a constant term smaller than 1% and linearity within 0.5% are required. 24 X_0 are required at $\eta = 0$ for longitudinal shower containment, with a relatively small radial occupancy of the calorimeter.

A low electronics noise, both incoherent and coherent, is also required; to achieve this,

one has to use low noise electronics and to keep the detector capacitance small.

- **angular resolution**

Due to an expected beam position spread along the beam axis of 5.6 cm, an angular resolution in the θ direction of $50 \text{ mrad}/\sqrt{E(\text{GeV})}$ is needed, which means high lateral segmentation and some longitudinal segmentation

- **particle identification capability**

for photon identification a jet rejection of 5000 with $\epsilon_\gamma = 80\%$ for $25 \text{ GeV} < p_T < 100 \text{ GeV}$ and an isolated π^0 rejection of 3 are required. For electron identification a jet rejection of 10^6 with $\epsilon_e = 90\%$ (with other detectors) for $20 \text{ GeV} < p_T < 50 \text{ GeV}$ is also required.

- **speed of response**

At nominal luminosity about 23 collisions every 25 ns are produced with about 7.5(7.9) charged (neutral) particles each per unit of η ($|\eta| < 5$). To cope with this pile-up noise a fast detector response and a fast readout are needed.

- **radiation hardness**

The region of the calorimeter at the largest rapidity ($\eta = 3.2$ for ATLAS) has to stand neutron fluences up to 10^{16} n/cm^2 and doses up to 500 kGy (over 10 years of operation at high luminosity)

Moreover the reconstruction of possible Z' with $M_{Z'} \sim 5 \text{ TeV}$ demands a very large dynamic range (up to 16 bits).

2. The accordion concept

The ATLAS collaboration has chosen a sampling technique for its electromagnetic calorimeter, with liquid argon as active medium and lead plates (sandwiched between two stainless steel foils) bent in accordion shape as passive material. Between two absorber plates, a three-layered copper-polyimide flexible printed circuit board, held in place by honeycomb spacers, provides the necessary drift field (high voltage is fed to the outer layers) and performs the signal readout (by capacitive coupling on the inner layer).

Figure 1. Three-dimensional view of the ATLAS calorimeters.

The barrel calorimeter covers the pseudorapidity range $0 < \eta < 1.4$ and lies inside the barrel cryostat, just behind the superconducting solenoid, between 1.5 m and 2 m radial distance from the beam axis.

The end-cap calorimeter covers the pseudorapidity range $1.375 < \eta < 2.5$ and lies inside the end-cap cryostat, between 3.6 m and 4.2 m from the interaction point (see figure 1).

2.1. Barrel calorimeter

Each half-barrel is made of 1024 absorbers [1], mechanically divided into 16 modules.

Each absorber has 13 folds, with the bending axes running parallel to the beam axis.

To have a uniform sampling fraction in the radial direction, the folding angle decreases from 92° to 68° and the fold length between bends increases going outwards, as shown in figure 2.

Figure 2. Transverse section through the active part of the barrel EM calorimeter, with a blow-up of a readout cell.

A uniform sampling fraction in ϕ could be obtained with sharp angles if the ϕ amplitude of folds were equal to $N=4$ times the absorber spacing. In practice, with the chosen absorber type, the maximum curvature radius is 3 mm. As a consequence a ϕ modulation of the response appears, though minimised with $N=4.067$.

To compensate for the decrease of sampling frequency as a function of η , which leads to a deterioration of the energy resolution, the sampling fraction is increased. To do this, two different lead thicknesses have been used for the barrel: 1.5 mm for $\eta < 0.8$, leading to a dE/dx sampling fraction f_{samp} of 0.252, and 1.1 mm for $\eta > 0.8$ with a f_{samp} of 0.282 with 2.1 mm gaps (the readout electrodes are $275 \mu m$ thick).

With the fast readout used [1,2], the most significant quantity for establishing the scale of a signal is the peak current corresponding to a given energy deposited in a readout cell, called *sensitivity* S . This quantity is readily calculated from the sampling fraction, the gap width and the value of the high voltage used (2.1 kV). For the barrel region $S = 2.74 \text{ nA/MeV}$ for $\eta < 0.8$ and $S = 3.08 \text{ nA/MeV}$ for $\eta > 0.8$.

2.2. End-cap calorimeter

Figure 3. Schematic view of an electromagnetic end-cap module. Only 3 absorbers out of 96 (in the outer wheel) are represented.

In order to accommodate the accordion geometry in this region, the absorbers are arranged as the spokes of a bicycle wheel, with the bending axes of the folds running perpendicularly to the beam axis. This geometry is such that the folding angle and the wave height must vary with the

distance from the beam axis. Due to mechanical limitations on folding angles, two absorber types are necessary to cover the whole pseudorapidity range: for the outer wheel, $\eta < 2.5$, 768 absorbers 1.7 mm thick and for the inner wheel, $\eta > 2.5$, 256 absorbers 2.2 mm thick are used for each end-cap, mechanically divided into eight wedge-shaped modules (a schematic view of these, including only few absorbers, is shown figure 3).

A constant lead thickness together with a varying liquid argon gap could result in a strong variation of the calorimeter response with η . However, with the fast readout used, a first order compensation as a function of η between f_{samp} (ranging from 13% to 30%) and g (ranging from 1 to 3 mm) is already achieved. On top of that, by feeding different η region with different values of the high voltage, ranging from 1 to 2.5 kV, a $\pm 5\%$ uniformity of the response can be obtained. This residual non-uniformity is corrected by software after careful calibration in test beam.

Figure 4. Sensitivity (see definition in the text) in the end-cap region vs η . No software correction applied.

3. Readout granularity

The readout electrodes have their copper layers segmented in order to give the required granularity both in η and in depth. Four electrode types are used, depending on η . The segmentation in η is designed in order to have a pointing geometry.

Figure 5. Longitudinal segmentation in the barrel region.

Three samplings in depth are implemented, with different lateral segmentation.

The first longitudinal sampling, of thickness $6 X_0$ (including the material in front), is meant to be used, beyond the energy measurement, for $\gamma - \pi^0$ and γ -jet identification and, together with the second sampling, for the reconstruction of the shower direction. Therefore this sampling is provided with fine granularity. Since in ϕ showers starting in front of solenoid are smeared by the magnetic field (2 T in the inner solenoid), finer granularity is given to the η coordinate. Therefore strips of pitch $\Delta\eta = 0.003$ to 0.006 , depending on η , are etched on the electrodes. In the ϕ

direction, 16 readout cells are ganged together, corresponding to a granularity of $\Delta\phi = 0.1$.

Figure 6. Readout granularity at $\eta = 0$.

The second longitudinal sampling, of thickness up to $24 X_0$ ($22 X_0$ for $\eta < 0.44$), is designed to contain e.m. showers with energy up to 50 GeV and therefore, for the whole η range, the cells are designed on the electrodes with a tapered geometry.

Its lateral cell size, $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, is derived from the Molière radius of the calorimeter, which is 2.5 cm.

The third longitudinal sampling, of thickness from $2 X_0$ to $22 X_0$, has a coarser granularity, i.e. 0.050×0.025 .

The region where the electrodes are provided with fine segmentation and which is therefore used for precise electromagnetic measurements, extends from $\eta = 0$ to $\eta = 2.5$.

For the region $\eta > 2.5$ there are only two samplings, of granularity 0.1×0.1 and their thickness corresponds to that of the second and third sampling, respectively, of the region at $\eta < 2.5$.

4. Barrel presampler

In the barrel region there are between $1.4 X_0$ and $3 X_0$ (depending on η) of dead material in front of the calorimeter. To be able to measure the energy associated to the low momentum particles produced in the interaction of electrons and photons with this material, a presampler detector was put in front of the barrel calorimeter. In the end-cap, since at a given E_T the average energy is larger than in the barrel, the presampler is less important and it was put only in the region $1.5 < \eta < 1.8$, where the material in front of the calorimeter is larger than $3 X_0$.

Figure 7. A barrel presampler module.

The barrel presampler is made of 32 identical azimuthal sectors per half-barrel, each sector containing eight modules (one of which is shown in figure 7), covering 0.2 in ϕ and 0.2 in η for a total of 512 modules.

The active layer is 11 mm deep.

The electrodes are alternated $235 \mu\text{m}$ thick double-sided cathode boards and $328 \mu\text{m}$ thick three-layered anode boards of copper-glass epoxy and are arranged perpendicularly to the beam axis. They provide a constant liquid gap of 2 mm with a high voltage of 2 kV. The readout granularity is one e.m. cell in η (0.025) and four in ϕ . For $\eta < 0.4$ the electrodes are slanted to reduce the impact position dependence of the response.

5. Linearity and Energy Resolution

The calorimeter is designed to have a linearity of the energy response better than 0.2% and, with the help of the presampler, a sampling term of the energy resolution of $\sim 10\%$, except in the region $1.5 < \eta < 1.6$, where a worse performance is expected. The constant term of the energy resolution receives different contributions.

From the mechanical point of view, the residual ϕ modulation and the non-complete hardware sampling fraction correction (in the end-cap) contribute 0.2% and 0.35%, respectively, even after a software correction is applied, due to shower fluctuations.

Lead plate thickness and gap thickness non-uniformity also contribute to the constant term. For a random distribution of thicknesses $\sigma(s)/s \sim 0.3 \sigma(\delta)/\delta$ where s is the signal amplitude and δ the lead thickness, which means $\sigma(s) = 0.15\%$ with $\sigma(\delta) = 8 \mu\text{m}$ on a 1.5 mm thick plate (a coherent change has an effect 2.5 times larger).

The sensitivity of the signal to the gap width spread is $\sigma(s)/s \sim 0.3 \sigma(g)/g$, which drives the requirement of the positioning of the absorbers during the stacking process to $50 \mu\text{m}$. Variations of gap width induced by lead plate thickness non-uniformities contribute as $\sigma(s)/s \sim 0.056 \sigma(\delta)/\delta$ so that $\sigma(\delta)/\delta = 100 \mu\text{m}$ corresponds to $\sigma(s)/s = 0.14\%$.

Taking into account the measurements performed on the different detector components produced so far and estimates of other systematic contributions, it is expected the total constant term of the energy resolution to be 0.55% in the barrel and 0.65% in the end-caps.

6. Production of the first full-scale module absorbers and stacking

To verify the correct functioning of the detector and to give the green light for the whole production, one barrel module and one end-cap module, in a configuration close to the final one, have to be tested in electron beams.

The absorber production chain is as follows.

The lead was laminated with the rolling technique from 10 cm thick blocks. Thickness mea-

measurements were performed at the factory with a X-rays detector, with a resolution of $\sim 5 \mu\text{m}$, allowing to discard lead foils when outside of tolerances. The absorbers were then cut to shape. The thickness measurements were repeated with an ultrasonic system (few microns precision and calibrated absolutely with a palmer). For all the plates the rms for a given nominal thickness is about $\sim 9 \mu\text{m}$.

Ultrasonic and X-ray measurements showed reasonable correlation.

After that, the absorbers were sorted and paired (only for the barrel) to anti-correlate thickness fluctuations for neighbour absorbers. The contribution of the thickness dispersion on the constant term of the energy resolution was then reduced from 0.3% to 0.15%.

The lead plates were then individually stacked between two $200 \mu\text{m}$ thick stainless steels foils (maximum dispersion $\pm 6 \mu\text{m}$) with a layer of pre-impregnated epoxy cloth (pregreg) in between and bent to the accordion shape. Figure 8 shows the bending press for the end-cap inner wheel absorber. The gluing of the sandwich is performed inside a press for the barrel, keeping it at 130° for 45 min with a pressure of 3.5 bars, and inside an autoclave for end-cap.

Figure 8. The bending press for the end-cap inner wheel absorbers.

At the end of the whole process, geometrical measurements of the absorbers were performed with a 3-d machine. All the measurements, such as lengths, bending angles and thicknesses were found to be very reproducible among absorbers and well within tolerances (e.g. widths to $200 \mu\text{m}$ and thicknesses to $40 \mu\text{m}$). A few global distortions (e.g. a twist in the outer wheel) at the level of 1 mm at most, were found, though they are not of concern for the calorimeter performance and they are anyway reduced after module stacking.

A barrel module stacking operation is shown in figure 9, together with the assembly jig.

Figure 9. Module stacking with the assembly jig.

Measurements of the gap dispersion after stacking gave for the barrel detector $50 \mu\text{m}$ which translates into a contribution to the constant term of less than 0.1%.

REFERENCES

1. ATLAS Liquid Argon Calorimeters Technical Design Report, CERN/LHCC/96-41
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