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Performance of a Liquid Argon Accordion Calorimeter with Fast Read-out

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Abstract

A prototype lead-liquid-argon electromagnetic calorimeter with parallel plates and accordion geometry has been equipped with high speed readout electronics and tested with electron and muon beams at the CERN SPS. For a response peaking time of about 35 ns, fast enough for operation at the future hadron colliders, the energy resolution for electrons is $9.6\%/\sqrt{E(\text{GeV})}$ with a local constant term of 0.3% and a noise contribution of $0.33/E(\text{GeV})$. The spatial accuracy achieved with a detector granularity of 2.7 cm is $3.7 \text{ mm}/\sqrt{E(\text{GeV})}$ and the angular resolution 12 mrad at 60 GeV.

1 Introduction

In order to increase further the possibilities of liquid argon (LAr) calorimetry for experimentation in the high rate environment of the future high energy hadron colliders (LHC and SSC), we have recently proposed a new “accordion” geometry [1], which combined with fast readout electronics provides a rapid response while allowing for a hermetic detector design. The successful test of an electromagnetic prototype with parallel plates demonstrated the validity of this concept [2]. For that occasion the calorimeter was equipped with preamplifiers fast enough to study the intrinsic speed limitation of the detector but the available bipolar shaping amplifiers had $t_p(\delta) \simeq 100$ ns (peaking time of the response to a δ current pulse), a value about four times larger than the anticipated optimum for an electromagnetic calorimeter operating in an LHC experiment.

As a further step of an extensive R&D activity for LHC [1, 3], the same prototype, slightly modified, was exposed again to test beams, this time equipped with dedicated bipolar shapers with $t_p(\delta) \simeq 20$ ns: the results are reported in this paper. The performances of a second prototype with a cylindrical accordion geometry and of an integrated LAr preshower detector will be presented in two forthcoming publications [4, 5].

This paper is organized as follows: section 2 describes the detector, the readout electronics and the calibration system, while the experimental setup and the data taking conditions for the test are covered in section 3; section 4 presents the results obtained with electron and muon beams and section 5 contains the conclusions.

2 The Accordion Prototype

2.1 Detector structure

In a previous paper [2] we extensively discussed the arguments for developing a calorimeter with accordion-shaped electrodes: this geometry allows to exploit the fast rise time of the ionization current produced by a shower in a noble liquid calorimeter by minimizing the charge transfer time from the detector to the readout chain.

The electromagnetic prototype (Fig. 1) has a section of about $30\text{ cm} \times 40\text{ cm}$ and a depth of 45 cm (about 25 radiation lengths). Transversely it is segmented in 12×15 readout cells in the $x \times y$ direction¹; longitudinally the left part (8 of 12 cells) is divided into two samplings ($2 \times 12.5 X_0$), while the right part is segmented into three compartments (7.8, 7.8 and $9.4 X_0$ respectively).

The calorimeter consists of “Kapton” readout electrodes alternated with converter plates. The latter are sandwiches of 1.8 mm lead clad in 0.1 mm stainless steel by preimpregnated fibreglass layers of 0.1 mm. Both the absorber and the Kapton sheets, which are separated by a LAr gap of 1.9 mm, have an accordion geometry with a fold width of 40.1 mm, a bend angle of 90° and a radius of curvature of 3 mm.

Each electrode consists of two double-sided copper-clad Kapton foils glued together. The copper layers were etched into longitudinal strips (24 mm wide and separated by a 1 mm gap) which define the vertical division in 15 readout cells. The outer copper strips of each electrode are at high voltage, while the inner strips are horizontally grouped together by three and DC coupled to a preamplifier. This determines the horizontal detector granularity of 27 mm.

¹The reference system (Fig. 1) has the z axis along the incident beam line, the y axis in the vertical and the x axis in the horizontal direction.

For the left part of the calorimeter the division into two equal longitudinal samplings was achieved by cutting each strip into two parts at mid depth. In this case the preamplifiers are installed on the front and back faces of the prototype. For the right part of the module, equipped with electrodes with three longitudinal segments, the front and back compartments are connected to preamplifiers as in the two sampling region, while the central section is connected to the back face of the calorimeter by a 2 mm wide strip (in this way the central section collects on average 10% of the energy actually released in the back compartment).

The ability of this calorimeter to produce a fast response to showering particles mainly relies on the low inductance of the circuit formed by the three horizontal strips in parallel and the preamplifier. The 2 mm wide connection of the central section to the back of the detector is in this respect not ideal, since it introduces an inductance of about 30 nH in series with the electrodes. However with a shaping time of about 20 ns this is acceptable, as confirmed by the present test beam results (section 4.1.2).

2.2 Signal processing

Three different types of charge preamplifiers were used for the readout chain of the prototype (Fig. 1). The bottom left region of the module was equipped, for comparison, with the electronics used in the previous test [2]: Si J-FET hybrids with 20 pF input transistor and 22 pF feedback capacitance resulting in about 25 Ω input impedance. They were followed by "slow" shapers ($t_p(\delta) \simeq 100$ ns) and peak sensing ADCs (Le Croy 2281).

The top left part was read out with new small size GaAs hybrids [6]. Their input capacitance is 80 pF, the feedback capacitance 33 pF, the input impedance 10 Ω and the power dissipation 54 mW. Some dispersion of the input impedance towards higher values was observed, especially when the preamplifiers were cold. From further investigation it was found that some device types are sensitive, at low temperatures, to large voltage excursions [7] and the problem was solved for a later test [4] by using a new batch of preamplifiers employing better MESFETs.

The right part of the module (three sections in depth) was equipped with new Si J-FET hybrids. The main differences from the Si set mentioned above are a bigger input transistor, a larger feedback capacitor (33 pF) and the fact that the transistors were bonded to the circuit without previously being encapsulated. The percentage of preamplifiers failing during cooling down was unexpectedly high (up to 20%), while the hybrids used in the first test had no failure. A new fabrication procedure which overcomes this problem has recently been found.

Both types of new preamplifiers were followed by specially designed fast shapers (Fig. 2). The connection between preamplifiers and shapers was achieved through 8 channel 50 Ω cables (6 m long) terminated at both ends.

The shapers consist of two differentiation and four integration stages, $(CR)^2-(RC)^4$, obtained by cascading two bandpass sections. These are built around a basic gain cell composed of a common emitter (Q2) and an emitter follower (Q3). The signal is buffered by Q1, to provide a clean termination of the line, differentiated by R1C1 and integrated by R2C2. It is then inverted by Q4 and integrated by R3C3 to give a negative output. A second stage with a similar pattern provides the remaining differentiation and two integrations. The output can drive -2.5 Volts on a 50 Ω load.

The shaper response to a δ current pulse is bipolar with a rise time (5% to 100%) of 18 ns: this value was chosen so as to minimize the sum of what would be the electronic and pile-up noise at a luminosity of $2 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$. The response to the triangular signal

coming from the detector has a peaking time of about 35 ns, with a dispersion controlled to about 1 ns.

The noise contribution of the shaper, dominated by the BFR91 input transistor and by the resistance in series with its base, amounts to about $1.4 \text{ nV}/\sqrt{\text{Hz}}$. Due to the rather large value of the feedback capacitance of the charge preamplifier (33 pF) and to the cable termination at both ends, the overall gain of the preamplifier, as seen at the shaper input, was relatively small. Therefore the noise from the shaper was not negligible compared to that due to the preamplifier.

In order to sample the shaped signal at its peak the shaper was followed by a fast and high precision Track and Hold (T&H). For that purpose we used a commercial circuit ², with a signal-to-noise ratio compatible with 12-bit ADCs. Its settling time is less than 12 ns and the dispersion in switching time from circuit to circuit less than 0.5 ns. The time jitter in the switching is specified to a few ps.

The voltage level following the "Hold" switching was digitized using a 2282 LeCroy integrating ADC operated with a gate width which was varied, depending on running conditions, from 60 to 120 ns. To avoid low frequency ripples (50 Hz), the signal from the T&H to the ADC was AC coupled.

In a later test [4] two new readout schemes aiming at reducing the amount of electronic components in the liquid argon have been studied: a single transistor at cold connected to the preamplifier at room temperature through a 6 m long 50 Ω cable and a 25 Ω transmission line sending the detector signals to the front-end electronics located outside the cryostat.

2.3 The calibration system

The prototype calibration was performed by injecting a known amount of charge at the preamplifier input through precision test capacitances (nominal value 22 pF) which were installed on vertical calibration boards perpendicular to the horizontal preamplifier mother boards. A voltage step, injected inside the cryostat with a 50 Ω terminated coaxial cable, was sent at the same time to fifteen calorimeter channels separated from each other by two non pulsed cells to allow for cross-talk studies. Close to the 50 Ω termination the signal was integrated by an RC network with a time constant of 120 ns, while at the sending end an inductance was introduced to give a frequency independent termination. The time constant of 120 ns simulates, on average, the charge collection time of the detector (400 ns); with fast shaping an RC value close to 400 ns would have been more appropriate to reproduce the current initial slope.

The test capacitances were measured by recording the output voltage of a same preamplifier moved over the entire calibration system. The precision achieved in this way was about 0.1 pF. The calibration accuracy was also affected by the uncertainty in the value of the RC time constant (less than 1% for the data presented here) and by the time delay (up to 2.5 ns) introduced by the pulse propagation from the top to the bottom of the calibration board. For this last reason the calibration system could not be used over the whole prototype surface without readjusting the relative time delay between the beam and the calibration trigger.

The cross-talk between adjacent calorimeter cells was determined by exploiting the calibration pattern described above. In the vertical direction, parallel to the calorimeter plates, it amounted to about 2% and could be mainly associated with the capacitance

² Acculin Inc Suite 204, 214 North Main Street Natick Mass 01760 USA

between contiguous strips on the Kapton board. In the horizontal direction, where each readout plane is separated from the following by a grounded converter plate, the cross-talk was smaller, varying typically within $\pm 0.5\%$. This residual value was attributed to the preamplifier board layout and to imperfections of the ground lines of the cables connecting the preamplifiers to the shapers. In a later test [4] these numbers were reduced to 1% and to $\pm 0.2\%$ respectively.

3 Test Beam Setup

3.1 Detector installation and beam line

The test module was installed inside the cryostat of the Helios experiment in front of two sections of the Helios uranium-liquid argon hadronic calorimeter [8]. The cryostat vessel consisted of a 3 mm thick stainless steel outer wall followed by 3 cm of vacuum and by a 2 cm thick aluminium wall. The space between this inner wall and the front face of the calorimeter was filled with low density "Rohacell" foam. The resulting amount of material in front of the prototype was about $1 X_0$.

The cryostat was mounted on a platform which allowed horizontal and vertical movements over ± 20 cm in each direction. A rotation around a vertical axis of maximum amplitude $\pm 4^\circ$ was also possible. Each movement was motor driven and an encoding system allowed to record and reproduce each position with the necessary accuracy.

The detector was exposed to electron and pion beams in the H6 beam line of the CERN Super Proton Synchrotron (SPS), where the maximum energy is 205 GeV. This beam line allows two successive momentum analyses. Above 120 GeV this feature was used to separate electrons from pions by means of their energy difference, after the first momentum analysis, due to synchrotron radiation. At 120 GeV and below electrons were selected by putting a thin lead target near the momentum slit and running the upstream part of the beam at 205 GeV. The momentum definition of the beam was estimated to be between 0.4% above 120 GeV (secondary beam) and 0.7% below (tertiary beam). Above 150 GeV the muon contamination in the beam was quite high: this feature was used to get electron and muon events in a concurrent way.

The direction of the incident particles was determined by means of three proportional wire chambers placed 8.2, 2.8 and 0.6 m upstream of the calorimeter. They allowed to extrapolate the particle impact point to the calorimeter with an accuracy of $280 \pm 30 \mu\text{m}$ in each direction.

3.2 The trigger

The T&H and the ADCs were installed close to the calorimeter and connected with cables of a few meters.

In order to gate the T&H early enough to measure the shaper output at its peak with some margin for timing studies, a fast trigger was necessary. The latter was organized in two levels. The first level was a coincidence of the signals coming from two fast scintillation counters installed close to the calorimeter, which strobed the T&H and started the ADC conversion. A second level, based on the information from other scintillators and sometimes as well from the calorimeter, was used either to generate a fast clear to the ADCs in case of a rejected event or to start the readout of the calorimeter and of the rest of the equipment.

The two small scintillation counters had an area of $3 \times 3 \text{ cm}^2$ and a thickness of 1 cm. A short light guide brought the light to Hamamatsu PM 1635 photomultipliers, chosen for

their short transit time (8 ns) and their good rise time (1.2 ns). One signal was delayed by 3 ns, so that the trigger coincidence was always started by the same counter. The overall time delay of the level 1 trigger from the particle crossing was 51 ns with a time jitter (estimated by comparing the signals from the two counters) of 210 ps.

3.3 Data taking conditions

The shaped signals obtained by injecting a calibration pulse into the input of a GaAs and a Si preamplifier are presented in Fig. 3. Also shown is the shaper output of a calorimeter cell hit by a 60 GeV electron. In the latter case, since the signal in one channel fluctuates from one event to the other, a digital oscilloscope in the single trigger mode was used; the flat tail, which corresponds to the first derivative of the triangular current pulse from the gap, has a length equal to the electron drift time (about 400 ns). The calibration signal has a slightly different shape: this is due to the fact that the calibration current has an exponential decay instead of a linear one and that the decay time constant was chosen too short (section 2.3), thus giving a somewhat earlier zero crossing time.

For data taking, the delay of the "Hold" command signal of the T&H system was varied in a window of ± 5 ns until the maximum energy in the calorimeter, as read out from the ADCs, was found. Then the timing of the calibration system was adjusted in the same way. Due to the limitations mentioned in section 2.3, this adjustment was valid only locally. The overall rms dispersion of the peaking time from channel to channel was about 1 ns: over the calorimeter area needed to reconstruct an electromagnetic shower, this dispersion did not significantly contribute to the energy resolution, as verified by comparing the performances obtained with various delays.

Each shaper card provides the analog sum of its 24 channels; a sum over a larger calorimeter area (4×24 channels) was used for the second level trigger as well as for timing studies. Using a constant fraction discriminator read out by a TDC, the time resolution of the calorimeter shown in Fig. 4 as a function of the beam energy was obtained. The distribution can be fitted with

$$\sigma_t = \frac{A}{\sqrt{E}} + \frac{B}{E}$$

where E is measured in GeV, σ_t in ns, $A=1.6 \pm 0.2$ ns GeV^{1/2}, $B=7.2 \pm 1.5$ ns GeV. This last term can be associated with the effect of the electronic noise.

In standard conditions the prototype was operated with a high voltage of +2 kVolts applied to the readout electrodes. However in order to investigate possible combined effects of the fast shaping and the slow electron drift in the gap, 90 GeV electron data were taken while reducing the high voltage down to 20 Volts; the resulting performances obtained with peaking times of 20 ns and 100 ns were then compared. From the convolution of the shaper response to a δ pulse with the triangular current from the detector, it is expected that when the high voltage (and therefore the electron drift speed) is increased, the signal grows more rapidly the shorter the shaping time. Going from 200 to 2000 Volts an increase in the fast-to-slow response ratio of 15% was observed, in agreement with the expectation. At lower voltages the signal from the calorimeter becomes too small to allow an accurate measurement.

In order to control possible drifts of the electronic response, a full calibration of the system was performed every few hours. Furthermore since the mean values of the ADC pedestals showed some small (a fraction of a count) erratic variations with time, to allow a closer monitoring the readout was randomly triggered a few times during each burst, concurrently with physics triggers. The gain of each channel was determined by fitting

the output of the relevant ADC as a function of the input charge (controlled by a 16-bit DAC) with a second order polynomial: the observed dependence was quite linear, the quadratic term amounting to typically 3% of the response at full scale. Using the electron beam energy as absolute scale, the sensitivity of the readout chain was found to be about 30 MeV per ADC count.

From the observed pedestal fluctuations the estimated electronic noise in the region read out with GaAs hybrids was about 75 MeV/channel, of which 60 MeV/channel due to the preamplifier and 45 MeV/channel due to the shaper: better input transistors for the latter have been recently found, which should significantly lower this second stage noise; we also aim at reducing the preamplifier noise to 40 MeV/channel, expected from scaling the value of 3.6 MeV/channel, measured in the test with slow readout [2], by the law $\text{signal/noise} \propto t_p(\delta)^{3/2}$ [9]. By comparing sums and alternate sums of pedestals over a large number of channels it was checked that the coherent (pick-up) noise was negligible inside a calorimeter area containing an electron shower. In the region equipped with Si preamplifiers, where due to the longitudinal segmentation in three samplings the cell capacitance is smaller, the measured noise was about 60 MeV/channel.

4 Test Beam Results

4.1 Response to electrons

The response of the prototype to electromagnetic showers was studied with electrons in the momentum range 5–200 GeV/c hitting the calorimeter at normal incidence. An angular scan taken at fixed position also allowed to determine the detector capability of measuring the direction of an incoming particle (section 4.1.5).

Single electron events were selected in the offline analysis by requiring signals compatible with one minimum ionizing particle in the proportional chambers and in the scintillation counters installed along the beam line in front of the prototype. Typically there were a few thousands of events per energy point, uniformly distributed over a spot of about $1.5 \times 1.5 \text{ cm}^2$.

In the calorimeter the electromagnetic showers were reconstructed, in each longitudinal compartment, by adding the energy deposited in a matrix of 3×3 contiguous cells around the readout channel with the highest signal. This nonet of towers, which covers an area of $8.1 \times 7.5 \text{ cm}^2$, contains most of the shower energy ($\sim 93\%$) and, compared to a larger size cluster (5×5 towers), contributes less noise (section 4.1.2) and is more suitable for physics in the high pile-up environment of an LHC experiment.

In the left part of the module, where each tower is divided into two longitudinal samplings, the mean energy fraction released in the first compartment decreases from 94% to 83% for electron momenta between 30 and 200 GeV/c. In the right part, with three segments in depth, at 30 (200) GeV/c the three sections contain on average 59%(45%), 37%(49%) and 4%(6%) of the shower energy. The observed leakage into the hadron calorimeter was negligible over the investigated energy range, amounting to less than 0.3% at 200 GeV.

Due to the presence of dead channels in the part of the prototype equipped with Si preamplifiers (section 2.2) only the region read out through the GaAs hybrids could be extensively studied and the results reported here, unless differently stated, refer to the latter.

4.1.1 Uniformity of response across a cell

One of the basic requirements of the electromagnetic calorimetry in an LHC/SSC experiment will be a response homogeneity able to ensure a constant term in the energy resolution of less than 1%, as needed by some physics channels of prime interest.

In the Accordion a potential source of response non-uniformity is the variation of the LAr thickness traversed by an incident particle as a function of its impact point along the x direction (Fig. 5). To minimize this effect the detector parameters were optimized through geometrical calculations and extensive full shower Monte Carlo simulations³.

The amplitude of the response variation, which is within $\pm 5\%$ for minimum ionizing particles at normal incidence, is expected to be smaller for electromagnetic showers due to their wider lateral size. This is demonstrated in Fig. 6 which shows the prototype response, over half a cell in x , to 90 GeV simulated and real electrons. A periodical modulation is visible: this reflects the calorimeter structure sketched in Fig. 5 with response maxima corresponding to peaks in the thickness of LAr traversed. Monte Carlo prediction and data have a similar pattern contained within $\pm 1\%$. The Accordion modulation has comparable shape and size at all energies, as shown by the rms amplitude of the x -response plotted in Fig. 7 versus the incident beam energy.

Since the energy resolution computed locally, inside a region of a few millimeters, is degraded by this effect when measured over a larger calorimeter area, an energy independent correction has been applied to the data above 20 GeV, using the x position reconstructed by the calorimeter. The residual rms amplitude of the modulation, also shown in Fig. 7, is about 0.2%. At 30 GeV the pattern starts to be confused due to limited statistics and the effect of the unfolding is modest. At still lower energies, where the resolution is dominated by the shower sampling fluctuations and by the electronic noise contribution, the correction becomes unimportant and therefore was not applied.

Along the y direction the Accordion behaves like a standard pad detector and the periodical structure observed in x does not appear. However the y -response is not flat over the whole cell, showing a drop of about 1.5% near the cell edges. This behaviour is largely due to the limited size of the nonet, which contains more energy when the electron hits the centre of the impact cell than when it impinges near its boundary. The effect is well reproduced by the Monte Carlo simulation of the prototype and has been eliminated in the data by an energy independent correction.

4.1.2 Energy resolution

The energy reconstructed in the calorimeter for 90 GeV/c incident electrons, corrected for the x and y dependent response described in the previous section, is shown in Fig. 8. A Gaussian fit to this distribution gives a resolution of 1.18% (1.10% after unfolding the beam spread).

The energy spectra produced by electrons of different energies have been fitted within $\pm 3\sigma$ around the maximum; after the quadratic subtraction of the beam momentum spread the resulting resolution (Fig. 9) can be parametrized by

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

where E is measured in GeV, and the sampling term ($a/\sqrt{E}$), the constant term (b) and the noise term (c/E) are added in quadrature.

³The Monte Carlo [10] reproduced all the details of the Accordion structure, including round corners and stainless steel cladding of the electrodes, while the charge collection mechanism was only introduced for the simulation of the pointing geometry prototype [4].

The result of the fit with three free parameters is

$$\frac{\sigma}{E} = \frac{9.61 \pm 0.24}{\sqrt{E}} \% \oplus (0.32 \pm 0.04) \% \oplus \frac{(0.326 \pm 0.015)}{E} \quad (1)$$

In this “local” resolution, computed over a calorimeter region of about $1.5 \times 1.5 \text{ cm}^2$, the constant term is largely due to the residual modulation of the corrected x -response discussed above. Not unfolding the response variation along the x and y coordinates would slightly increase the constant term. The fit would give in this case

$$\frac{\sigma}{E} = \frac{9.84 \pm 0.38}{\sqrt{E}} \% \oplus (0.62 \pm 0.04) \% \oplus \frac{(0.316 \pm 0.017)}{E} \quad (2)$$

The noise terms in (1) and (2) are compatible with the value of about 75 MeV per channel quoted in section 3.3, summed up incoherently over the eighteen channels of the nonet. Reconstructing the shower energy in a matrix of 5×5 cells per longitudinal compartment yields a comparable resolution, except for a larger noise term ($483 \pm 17 \text{ MeV}$) consistent with the increased number of channels included in the electron cluster.

By rotating the platform supporting the prototype (section 3.1), the beam incidence angle (ϑ) in the horizontal plane was varied between $\pm 4^\circ$ around the direction perpendicular to the calorimeter; for 90 GeV electrons it was observed that the energy resolution, uncorrected for the response variation along x , improves by about 15% when away from normal incidence. This is the consequence of a smoothing of the periodical pattern shown in Fig. 5 due to the misalignment between the edges of the Accordion folds and the particle direction.

In our previous test [2] performed with slow readout electronics, where the noise was about 4 MeV/channel, we measured an energy resolution of

$$\frac{\sigma}{E} = \frac{10.1 \pm 0.4}{\sqrt{E}} \% \oplus (0.2 \pm 0.2) \% \quad (3)$$

This result was obtained without correcting the energy response as a function of the electron impact point and therefore should be compared with (2). In (2), apart from the anticipated appearance of the noise term, the constant term is somewhat larger than in (3). After observing that this term was determined with less precision in the previous test, due to the lack of energy points above 150 GeV, the difference can be attributed to two factors: a small misalignment of the prototype from the plane orthogonal to the beam direction in the previous test, which resulted in a slightly less pronounced response variation along the x direction (see above), and some dispersion in the preamplifier rise time from channel to channel (section 2.2) in the present test, which prevented the best possible intercalibration of the nonet cells.

An energy scan between 20 and 200 GeV was taken also in the calorimeter region equipped with Si preamplifiers (three longitudinal samplings), sending the beam to an area where the effect of the dead channels was minor. Using the same x and y response correction, the resolution is given by

$$\frac{\sigma}{E} = \frac{8.72 \pm 0.49}{\sqrt{E}} \% \oplus (0.47 \pm 0.05) \% \oplus \frac{(0.324 \pm 0.036)}{E} \quad (4)$$

At each energy the resolution is comparable to, or slightly better than, that measured in the GaAs region except for the 200 GeV point, which determines the somewhat larger

constant term than in (1). The total noise in the electron cluster is compatible with the value of about 60 MeV/cell quoted in section 3.3.

4.1.3 Linearity of response

At each momentum setting, the mean electron energy deposition in the calorimeter was taken to be the peak of a Gaussian fit. To minimize time variation effects, the electronic pedestals for each run were obtained from the "in-burst" random events (section 3.3).

Fig. 10 shows the calorimeter response to electrons as a function of the incident beam energy. The response has been normalized by the nominal beam energy at each setting and the calorimeter energy scale has been determined by the 90 GeV point. The errors include an uncertainty of ± 100 MeV due to imprecise knowledge of the magnet hysteresis as well as the effect of possible systematic gain drifts in between two calibration runs.

The detector response is well within $\pm 1\%$ of the nominal beam energy including the low energy points. The linearity is slightly improved when a 5×5 tower cluster is used; this can be attributed to a weak energy dependence of the lateral shower containment.

4.1.4 Space resolution

Good position and angular resolution is required to cover the full range of possible physics signatures at the future hadron colliders. From this point of view, the Accordion concept offers a high performance-to-granularity ratio.

While along the y direction the space resolution is dictated by the granularity, as for a conventional pad calorimeter, in the x direction (across the Accordion folds) the shower core is shared among neighbouring cells, which allows a more precise measurement of the shower centre of gravity.

The shower position was determined by the first moment of the energy distribution in a nonet of cells using only the first sampling. For 90 GeV electrons the correlation between the reconstructed shower position and the impact point extrapolated from the beam chamber system is shown in Fig. 11a and 11b for the x and the y directions respectively. Along x the correlation is linear and the position resolution is independent of the particle impact point on the cell. The difference between these two measurements is given in Fig. 11c. After subtraction of the beam chamber resolution (section 3.1), the position accuracy is $\sigma_x = 365 \pm 26 \mu\text{m}$.

The x position resolution improves with increasing energy. This behaviour, shown in Fig. 12, is linear versus $1/\sqrt{E}$. A fit to the data yields

$$\sigma_x = \frac{(3.74 \pm 0.02)}{\sqrt{E}} \text{ mm} + (-0.03 \pm 0.01) \text{ mm}$$

where E is expressed in GeV.

Along the y direction the usual behaviour is observed: the reconstructed position of particles hitting inside a cell is shifted towards the cell centre, while it is unbiased for those impinging on the boundary between adjacent channels. A functional fit to the relation between the measured (y_{CALO}) and the extrapolated (y_{CHAMBER}) impact point, of the form

$$y_{\text{CALO}} = a \cdot \tan\left(\frac{y_{\text{CHAMBER}}}{b}\right) + c$$

yields $a = 0.165$, $b = 0.452$ and $c = 0.0035$, with all quantities expressed in cell units, and has been used to correct the particle y position reconstructed by the calorimeter (a slight energy dependence of these parameters was not included). The resolution of the

corrected position for particles hitting over the whole cell (Fig. 11d and 12) can be fitted as

$$\sigma_y = \frac{(4.79 \pm 0.01)}{\sqrt{E}} \text{ mm} + (0.04 \pm 0.01) \text{ mm}$$

4.1.5 Angular resolution

The longitudinal segmentation of the Accordion calorimeter can be used to obtain a measurement of the particle direction: the shower development inside the detector is oriented at the same angle as the incident electron. If a centre of gravity measurement is performed in the different longitudinal samplings, the displacement between the obtained values is proportional to this angle.

A study was performed with 90 GeV electrons impinging on the calorimeter at different angles in the x - z plane. The shower centre of gravity was determined separately for a nonet of cells in the first and second samplings. The mean of the difference $x_1 - x_2$ between the two values is proportional to the incident beam angle ϑ . A fit gives

$$x_1 - x_2 = (125 \pm 8) \text{ mm} \times \vartheta$$

with x_1 and x_2 expressed in mm and ϑ in rad. The 125 mm can be interpreted as the average difference between the longitudinal shower barycentres in the two samplings. Therefore, after an initial calibration to determine this factor, a measurement of $x_1 - x_2$ allows to deduce the angle of any electromagnetic particle.

The angular resolution can be extracted from the distribution of $x_1 - x_2$, which is shown in Fig. 13 for 90 GeV electrons. A Gaussian fit to the data gives $\sigma_{x_1 - x_2} = 928 \pm 4 \text{ } \mu\text{m}$ and therefore the angular resolution is $7.4 \pm 0.5 \text{ mrad}$.

The longitudinal segmentation of the prototype was not optimized for angular measurements: in fact, due to the limited penetration of the showers in the second sampling, the barycentre reconstructed in the back compartment is critically affected, at low energy, by the electronic noise. In order to limit this effect, a minimum energy deposition of 1 GeV was required in this sampling. Using 125 mm as an energy independent proportionality factor between $x_1 - x_2$ and ϑ , the angular resolution plotted in Fig. 14 as a function of $1/\sqrt{E}$ was obtained. A fit to the data yields

$$\Delta\vartheta = \frac{47.5}{\sqrt{E}} \text{ mrad} + \frac{364.6}{E} \text{ mrad}$$

where the second term reflects the electronic noise contribution. A typical value of the resolution is 12 mrad at 60 GeV.

In the y direction an angular accuracy of about 30% worse than in x was obtained, consistently with the poorer position resolution (section 4.1.4).

4.2 Response to muons

The prototype response to minimum ionizing particles was studied by using muon data taken together with electron events in the high energy runs.

Clean muon events were selected by requiring an energy deposition of less than 5 GeV in the hadron calorimeter and smaller than 10% of the beam energy in the Accordion prototype. These two cuts allowed to reject pions and electrons in the beam.

Since the noise is not negligible as compared to the muon signal in one channel, the particle impact cell in the calorimeter was determined by using the information from the beam chamber system instead of looking for the channel with the highest energy.

Due to the accordion geometry the signal released by a minimum ionizing particle is always shared between two contiguous cells in the x direction. Therefore the muon energy was reconstructed, in each longitudinal sampling, by adding the signals from the pair of neighbouring cells in x closest to the particle impact point. In the y direction the muon energy is generally well contained in one channel, except near the cell boundary where a fiducial cut was applied.

Fig. 15 shows the energy deposited in the calorimeter by 200 GeV muons incident in the prototype region read out by Si preamplifiers; the energy scale of the electron data has been used. The muon peak position averaged over different runs is 450 ± 15 MeV, equally distributed among the longitudinal compartments. The 20% lower value quoted in our previous paper [2] is only partly explained by the lower muon energy (100 GeV). The Monte Carlo prediction, normalized to the peak position of the data, well reproduces the shape of the experimental distribution.

The electronic noise was determined in the same muon runs by evaluating the energy contained in clusters of 4 (6) channels in the GaAs (Si) region far away from the particle impact point. The σ of the resulting distribution is 155 MeV in the GaAs region and 140 MeV in the Si region, in agreement with the values of 75 MeV/cell and 60 MeV/cell mentioned in section 3.3 and 4.1.2.

The resulting signal-to-noise ratios are 2.9 (GaAs region) and 3.2 (Si region).

5 Conclusions

The first prototype of a new electromagnetic calorimeter with an accordion geometry was successfully tested in 1990. The results presented in this paper demonstrate that the main detector performances are preserved when the calorimeter is equipped with fast electronics (peaking time of the shaped response of about 35 ns) adequate for experimentation at the LHC. In particular an energy resolution of $9.6\%/\sqrt{E(\text{GeV})}$ with a local constant term of 0.3% and a noise contribution of $0.33/E(\text{GeV})$ has been achieved for electrons. The measured space accuracy is $3.7 \text{ mm}/\sqrt{E(\text{GeV})}$ and the angular resolution is 12 mrad at 60 GeV.

Part of the future programme of our R&D activity is the test in 1992 of an electromagnetic and hadronic module of size $\Delta\phi \times \Delta\eta \simeq 22.5^\circ \times 0.5$ [3], conceived as a full sector of a large scale calorimeter for LHC.

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Figure 1: A schematic view of the prototype with its equipment.

Figure 2: The circuit diagram of the fast bipolar shaping amplifiers.

Figure 3: The shaped signal of a) a calibration pulse injected into a GaAs preamplifier, b) a calibration pulse injected into a Si preamplifier, c) a 60 GeV/c electron hitting one calorimeter cell. The scales are 20 ns/div. (horizontal) and 100 mV/div. (vertical) in a) and b); 50 ns/div. (horizontal) and 50 mV/div. (vertical) in c).

Figure 4: The time resolution of the calorimeter response as a function of the incident beam energy (trigger resolution unfolded). The line is a fit to the experimental points (see text).

Figure 5: The total liquid argon thickness, in radiation lengths, as a function of the position along the prototype x view (Monte Carlo simulation). The dotted lines delimit a $\pm 5\%$ band around the mean value.

Figure 6: The calorimeter response, normalized to the mean value, as a function of the electron x position over half a cell for a 90 GeV beam. Closed circles: experimental points. Open circles: prediction of a full shower Monte Carlo simulation of the Accordion geometry.

Figure 7: The rms amplitude of the response modulation along x as a function of the incident electron energy before (open circles) and after (closed circles) unfolding the periodic pattern.

Figure 8: The measured energy spectrum of 89.77 GeV electrons as obtained after correction for the response variation with the particle impact point. The solid line is a Gaussian fit.

Figure 9: The energy resolution of the calorimeter at different electron energies (the error bars are smaller than the data points). The dotted line is a three parameter fit (see text).

Figure 10: The normalized calorimeter response as a function of the incident beam energy (fixed to 1 at 90 GeV). The shower has been reconstructed in the calorimeter by using a cluster of 3×3 (open circles) or 5×5 (black symbols) towers.

Figure 11: The position reconstructed in the calorimeter for 90 GeV electrons vs the impact point extrapolated from the beam chambers in the x (a) and y (b) direction. Difference between these two quantities along the x (c) and y (d) view (corrected measurement). The full lines are Gaussian fits to the experimental points.

Figure 12: The accordion position resolution in x and y versus $1/\sqrt{E}$. The dashed lines are linear fits to the data points (see text).

Figure 13: The difference in the x direction between the shower barycentres measured in the two longitudinal samplings for 90 GeV electrons hitting the calorimeter at normal incidence. Superimposed is a Gaussian fit.

Figure 14: The angular resolution of the calorimeter at different electron energies. The line is a fit to the experimental points (see text).

Figure 15: The energy spectrum reconstructed in the calorimeter for 200 GeV muons incident in the region equipped with Si preamplifiers. Full line: data. Black symbols: Monte Carlo simulation. The dot-dashed line is the distribution of the electronic noise (see text).