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PERFORMANCE OF A LIQUID ARGON ELECTROMAGNETIC CALORIMETER WITH A CYLINDRICAL ACCORDION GEOMETRY

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ABSTRACT

A prototype of a lead liquid argon accordion calorimeter with two types of cylindrical geometry was constructed and equipped with high speed readout electronics. The energy resolution for electrons is $10\%/\sqrt{E(\text{GeV})}$ with a local constant term of 0.65%. The resolutions obtained for position and angular measurements are given.

1. INTRODUCTION

Experimentation at LHC requires an electromagnetic calorimeter with a fast response and a good granularity while maintaining hermeticity. An attempt to satisfy these criteria with the liquid argon sampling technique has led to the test of a novel geometry, where the absorber and the readout plates are fabricated with an accordion shape. A prototype of this kind has already been built and tested at CERN in 1990 (Ref. 1).

The parallel geometry of this prototype cannot be used in a calorimeter for LHC which must surround the interaction region in an azimuthally symmetric way and extend to large pseudorapidity for the barrel part, with towers preferably pointing to the centre of the interaction.

This paper describes the construction and performance of a second prototype built to test two possible solutions to the problem of cylindrical geometry. The first solution consists in simply opening up the absorber and readout plates to make them converge towards the interaction point. As a consequence, the sampling fraction varies through the depth of the calorimeter. In the second solution a tapered cladding is added to the absorber plates to ensure a constant thickness of the argon gap. This study is part of an R&D program for the design of a complete liquid argon calorimeter for a LHC detector (Refs. 2 and 3)

2. CONSTRUCTION OF THE PROTOTYPE

The first electromagnetic calorimeter prototype, described in Ref. 1, had the following characteristics. Its front face had a width of 40 cm divided into 16 columns of cells and a height of 37.5 cm divided in 15 rows of cells. To limit the complexity of the mechanical construction at this early stage, the folds of the accordion were identical, with the same length between folds and the same bending angle. The absorber and the readout plates were placed parallel in an overall frame.

The electronics used to test the first prototype in 1990 had a time response of about 140 ns which is too slow to match the 15 ns bunch spacing at LHC and the pile-up induced by an average of 20 interactions per beam crossing at luminosities of the order of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Faster electronics with a peaking time response $t_p(\delta)$ of 18 ns to a delta current pulse was built and tested on the same prototype in the first half of 1991. The results, given in Ref. 4, show that the performances of the parallel accordion structure are well preserved with a fast shaping of the collected ionisation signal.

The rate of interactions expected from pp collisions at LHC with high luminosity is such that the design of an electromagnetic calorimeter would favour a fine granularity. For example, the transverse dimensions of 2.7 by 2.5 cm² of the first prototype would be appropriate for a barrel calorimeter of about 1.3 m radius and have been retained for the construction of the present prototype.

2.1. Cylindrical geometry with opening argon gap

The accordion design can easily be adapted to a pointing geometry in one direction, namely the direction along the folds of the absorber and readout plates. In this direction, the projectivity of the cells towards the interaction point can simply be ensured by a proper etching of the readout strips, such a design will be implemented in a future prototype (Sec. 2.2 and Ref. 3). This direction would correspond to the rapidity axis in a LHC calorimeter and will be referred to as the y axis in this paper.

In the other direction, transverse to the absorber plates and referred to as the x axis, the simplest way to achieve a cylindrical geometry is to open up the absorber plates around the beam line with the folds parallel to it. The angle between two adjacent absorber plates is then $\alpha = 2 \pi/N$, where N is the number of plates necessary to span the full calorimeter azimuth. In the design of the first prototype, the accordion pitch and the liquid argon gap were optimized to reduce as much as possible the non-uniformity of the energy response in the direction transverse to the plates as shown in Fig. 4 of Ref. 1. When consecutive plates are rotated, this optimisation can only be satisfied at a given depth of the calorimeter, namely where the argon gap thickness is kept at its nominal value of 1.9 mm. With the guidance of the results of GEANT simulations, this point was placed at about 20 cm from the entrance face of the calorimeter roughly at the maximum of high energy electron showers. For the present absorber plates, and for an inner barrel radius of 130 cm this corresponds to $N = 1056$ or $\alpha = 0.341^\circ$.

One half of the prototype was assembled with this geometry. This is shown in the lower part of Fig. 1a. The absorber plates, identical to the ones of the 1990 prototype, were produced with the same technique and tooling as described in Ref. 1. These plates

were made of a 1.8 mm lead sheet sandwiched between two 100 micron stainless steel plates. The steel plates were glued to the lead with a sheet of prepreg, made of a layer of 100 micron epoxy impregnated glass cloth.

This geometry has the obvious weakness that the thickness of the argon gap increases along the depth of the calorimeter. It is 1.44 mm at the entrance and 2.39 mm at the exit so that the ratio of the argon to the lead thickness increases by a factor 1.66 and the electric field in the gap decreases in the same proportion. As a consequence, one might expect that the fluctuations of the shower development in the depth of the calorimeter induce a worsening of the energy resolution. As anticipated from the GEANT simulations and as the result discussed in section 4 shows, the performances of such a calorimeter can be restored to the level observed with the parallel plate prototype. This can be achieved by giving a slightly different weight to the energy measured in the front and back compartments of the calorimeter.

2.2. Cylindrical geometry with compensated argon gap

The variation of the absorber to argon thickness ratio implied by the type of construction described above, can be corrected mechanically at the price of a complication in the absorber plate construction.

A new set of absorber plates was built with the same technique and with the same tooling used for the fabrication of the 1990 prototype plates, but one more layer of prepreg was added every two folds. The prepreg total thickness on each side was then 0.1 mm at the beginning and 1.0 mm at the end. The same choice, as for the opening gap, was made for the angular pitch between the absorber plates since most of the radiation length is in the lead. The width of the argon gap was then constant and equal to 1.44 mm. A sketch of these compensated gaps is shown in Fig. 1b, and their assembly is shown in the upper part of Fig. 1a.

A solution which would preserve the thickness uniformity of both the lead absorber and the argon gap at all depths of the calorimeter will be tested in a third prototype in 1992.

2.3. Electrode readout plates.

The electrode readout plates consisted of two kapton sheets clad with copper and glued together. The middle copper layers were divided into strips of 24 mm constant width separated by 1 mm. The outer layers reproduced the same strip pattern and were

connected to the high voltage supply. The kapton served as blocking capacitors. More details are given in Refs. 1 and 4.

Two different types of kapton readout circuits were used. In the first, the strips were split in their middle. This allowed dividing the calorimeter cells into two compartments in depth. Taking into account the opening up of the absorber plates, the first compartment was 13.4 radiation length deep and the second 12. In the second type of readout electrodes, the strips were divided in three sections thus providing three compartments in depth, 8.6, 7.8 and 9 radiation length respectively. The middle section was connected to the back by a 2 mm wide strip running in between the strips of the third section.

The strips corresponding to three adjacent readout electrodes were connected together so that the mean cell width in x was 2.7 cm.

2.4. Prototype assembly

The prototype was assembled with the plates vertical, along the y axis. In the horizontal direction, the x axis, the left half of the calorimeter was obtained by assembling 19 compensated absorber plates interleaved with 18 of the readout plates with two segments in depth. This side of the prototype is called the compensated gap calorimeter. It was subdivided into 90 cells, 6 in the horizontal direction and 15 in the vertical direction (Fig. 2).

For the right half, 18 constant thickness plates were used, interleaved with 18 of the readout plates with three segments. This side is called the opening gap calorimeter, and was also divided into 90 cells in the same way. The readout located at the border between the 2 halves was peculiar since the gap on its left had a constant thickness, while the gap on its right had an increasing thickness. For this side, the readout plates with three sections in depth were used.

A preshower prototype of an area covering about 2×2 cells was located in front of the left part of the calorimeter as indicated in Fig. 2. The design and performance of this prototype will be given in a forthcoming paper (Ref. 5).

As for the first prototype, the signal was collected at the front and the back of the calorimeter. The calibration system consisted of one printed circuit per vertical row of cells which held 22 pF injection capacitors and an RC network. The preamplifiers were mounted on horizontal motherboards which connected the three adjacent electrodes, distributed the power and carried the amplified signal to the cable connectors located on

the sides. Both the calibration and the preamplifier boards were identical to those used on the first prototype, except for the dimensions in the horizontal direction which had to be reduced for the front and increased for the back.

3. ELECTRONIC READOUT

Four different schemes of front-end electronics were implemented on the prototype. For the first two, charge preamplifiers were mounted directly on the front and rear face of the calorimeter and used at liquid argon temperature. One type of preamplifier hybrid consisted of MESFET GaAs transistors and the other of J FET silicon transistors. The third type of electronics consisted of a single transistor replacing the preamplifier which was then placed outside the cryostat. In the fourth scheme, the single transistor was removed and the calorimeter cells were directly connected to the cable (Ref. 6). The location on the calorimeter of the various types of electronic readout can be seen in Fig. 2.

3.1. Cold preamplifiers

The charge preamplifiers were mounted directly on the detector to minimize the charge transfer time from the electrodes to the preamplifier. The GaAs hybrids had an input capacitance of 80 pF, a feedback capacitance of 33 pF, an input impedance of 10 Ohms. The corresponding values for the Si J Fet hybrids were 50 pF, 33 pF and 20 Ohms respectively. Each preamplifier was followed by a 6 m long 50 Ohm cable and by a shaper amplifier at room temperature which had a bipolar filter made up of 2 differentiations (CR) and 4 integrations (RC). The peaking time response $t_p(\delta)$ of the shaper for a delta current pulse was 18 ns (Ref. 6), which corresponds to a 35 ns peaking time for the triangular shape of the liquid argon current pulse.

At this shaping time, the dominant noise source is the channel thermal noise of the input transistor with some contribution of the $1/f$ noise in the case of the GaAs hybrides (Ref. 7). Laboratory measurements of the equivalent noise charge (ENC) at the input with a 400 pF detector capacity are 18000 e^- rms for the GaAs version and 21000 e^- rms for the Si version.

Due to the combined effects of the low preamplifier gain, and of the loss of signal in the attenuation and the termination of the connecting cable, the contribution of the shaper to the noise was not negligible. The total ENC of the system was 23000 e^- rms with GaAs hybrids. The corresponding noise measured in the calorimeter was about 72 MeV, including the ballistic deficit.

No results were obtained with the Silicon preamplifiers due to failures in the connections of the hybrids obtained from a new manufacturer. Since then, this problem was avoided by using preamplifiers of the original supplier.

3.2. Single transistor

Another solution, which reduces the number of electronic components in the Liquid Argon, consisted in a single common gate transistor (JFET or GaAs) in the cryostat driving a 6 m long 50 Ohm cable connected to the preamplifier at room temperature. This single transistor has low input impedance ($1/g_m = 20$ Ohms), and therefore a short charge transfer time. The preamplifier, which matched the 50 Ohm line, was followed by the same $(CR)^2(RC)^4$ shaper as above.

In this configuration the main sources of noise are the thermal noise of the Single Transistor and the series noise of the preamplifier terminating the line. The total measured noise in this configuration was $25000 e^-$ and corresponded to about 78 MeV per channel measured in the calorimeter. This included a coherent noise contribution of about 10 MeV per channel.

3.3. Zero transistor

In this configuration, a 6 m long 25 Ohm transmission line connected the detector to the front end electronics at room temperature. The 25 Ohm impedance seen by the detector leads to an acceptable ballistic deficit.

In this case the first electronic stage was a non integrating current amplifier with feedback to the base, adjusted to terminate the line by its characteristic impedance. This line receiver was followed by a unipolar filter with one differentiation and two integrations. As there is no current integration in the preamplifier, the output signal is bipolar with a peaking time for a delta current impulse at the detector of 18 ns.

With this shaping time and a 400 pF detector capacity, the 6 m long cable did not increase the noise significantly. Fig. 3 shows the results of a theoretical calculation of the ENC as a function of the length of the 25 Ohm line, for a detector capacity of 400 pF and peaking times of 20, 50 and 100 ns. When the time delay of the transmission line is of the order of, or longer than the shaping time, it is the characteristic impedance and not the capacitance of the line which determines the noise contribution. The calculation were made for a preamplifier with a noise spectral density of $0.5 \text{ nV}/\sqrt{\text{Hz}}$ and an ideal line. As seen in the figure, the noise is not increased by adding a 6 m cable for a 20 ns peaking

time. There are in fact 2 factors which can deteriorate the signal to noise ratio. The first is the time dispersion due to skin effect which delays part of the input charge so that it cannot contribute to the output signal. The second is the skin effect resistance which generates thermal noise. However, since most of the cable is in the Liquid Argon, both effects are reduced.

Since the line receiver was at room temperature, bipolar transistors, with good noise performance, could be used. For the version used in this test, the line receiver input transistors were two BFR91 in parallel so that the base spreading resistance $R_{bb'}$ was equal to 15 Ohms. The noise was comparable to that of the cold preamplifiers, and its measured value amounted to about 20000 e^- at a shaping time of 18 ns. The corresponding noise measured in the calorimeter amounted to 83 MeV. This value includes a contribution of coherent noise of about 20 MeV due to pick-up noise from unshielded wires penetrating the Faraday cage, defined by the cryostat.

A new version of the line receiver was developed using NE856 transistors with $R_{bb'} = 4$ Ohms. The measured series noise is 0.38 nV/ $\sqrt{\text{Hz}}$ corresponding to 8,5 Ohms of noise resistance. This solution will soon be tested on the prototype in a beam at CERN.

3.4. Track and hold, ADC

The shapers were followed by a track and hold circuit (T&H), which sampled the shaped signal at its maximum with a common trigger. The timing dispersion of the ionisation and calibration pulses of all the channels were small compared to the width of the shaped signals. The output of the T&H was then digitized in a 2282 LeCroy charge integrating ADC.

4. TEST BEAM RESULTS

The prototype was inserted in the HELIOS cryostat in the H6 beam line at the CERN SPS. The cryostat was mounted on a platform which could be remotely moved horizontally and vertically and rotated by $\pm 4^\circ$ around its vertical axis. The cryostat was rotated to maintain the beam perpendicular to the face of the calorimeter towers to simulate particles coming from an interaction point.

The beam telescope consisted of two fast scintillator trigger counters and three multiwire proportional chambers each measuring x and y coordinates.

4.1. Data taking

The data used in the present analysis were taken in three parts of the calorimeter (see Fig. 2) : in the GaAs and zero transistor areas of the compensated gap region; and in the single transistor area of the opening gap region. No data were taken in the region with silicon preamplifiers for reason explained in section 3.1.

For each location, electron data were taken at various beam energies between 20 GeV and the maximum energy of 197.5 GeV. Data were also taken to measure the angular resolution of the calorimeter in both the compensated and opening gap regions.

4.2. Monte Carlo simulations and comparisons with the data

The detector response of the two geometries was simulated using the GEANT 3.14 package (Ref. 8). The absorber plates of the opening gap geometry were approximated by a 2.2 mm thick material composed of an homogeneous mixture of 1.8 mm lead, 0.2 mm of steel and 0.2 mm of prepreg. To reproduce the compensated gap absorber, this 2.2 mm thick material was cladded with a layer of glass-epoxy with increasing thickness. The readout electrodes were also approximated by a 400 micron sheet of an equal mixture of copper and kapton.

The calculation of the calorimeter response requires a detailed simulation of the charge collection and the pulse shaping since the current distribution as a function of time depends upon the geometry of the gaps in particular in the case of the opening gap. Ionisation tracks of the shower development in the liquid argon were simulated with a cut-off of 100 KeV on both the electron and the photon energies and were recorded to allow for the study of the charge collection. This information consisted of the starting point coordinates, the direction, the length and the energy loss of each track segment in the liquid argon. A 90 GeV shower represented 4.5 Mbytes of information and required about 650 seconds processing time on a 3090 IBM. Such information was then used, for example, to give a picture of the electrons present in the development of a typical shower as shown in Fig. 4.

The simulation of the charge collection was performed in a subsequent program. Each track segment was subdivided in smaller steps of 100 microns and the energy release was assumed uniform along the track segment. The contribution of all the steps to the current were added by using a grid which takes into account the field, the drift velocity and the shaping time distribution. The electric field was computed with the PRIAM program, which uses a mixed finite elements method (Ref. 9).

The time distribution of the signal pulse after the fast shaping electronics was calculated (Fig. 5) and compares well with real signal as in Fig. 3 of Ref. 4. For this comparison, the simulated pulse was limited to the contribution of the fold corresponding to a 1.9 mm argon gap.

4.2.1. Dependence of the energy as a function of the shower depth.

For most of the results which will be shown, the energy of the showers were collected by summing the contribution from a matrix of 3×3 cells centered on the highest energy cell.

As mentioned in Section 2.1, the total charge measured in the opening gap calorimeter shows some dependence on the depth at which the shower develops. This depth could, for example, be parametrized by the fraction of the energy deposited in the front or the back sections of the three compartments. Figs. 6a and 6b show the total energy normalized to its mean value for 90 GeV electrons, as a function of these two fractions. The points with the crosses are the results of the GEANT simulations which agree well with the histograms representing the data. If the ionisation signal of the electrons were integrated over the full length of the drift duration, the signal would look like the dashed lines of Fig. 6 obtained with the simulation. The slope of these lines can be explained by the fact that the sampling fraction of argon to absorber increases with depth thus resulting in a larger amount of charge for showers with a late development. For fast pulse shaping, the response depends more on the initial current and thus should change much less with the depth of the shower development. However, as the gap thickness increases, the electric field decreases. Consequently the drift velocity, which is not fully saturated, is reduced resulting in a lower response for late showers.

In the compensated gap calorimeter, the variation of the collected energy as a function of the depth of the shower is smaller, as can be seen in Fig. 7 compared with Fig. 6. The agreement of the GEANT simulations with the data is also good. In this case, the total charge was not shown, since the time distribution of the ionisation does not depend on the depth.

The longitudinal fluctuations of the shower profile in the opening gap calorimeter (Fig. 6) induces a constant term in the energy resolution. This term, at the level of 1%, could be greatly reduced by a first order correction which consisted of one weight per longitudinal compartment. At 90 GeV the relative weights optimizing the energy resolution were 0.86, 1.0 and 1.23 for the three compartments respectively. Their variation over the range of energies was very small so they were kept fixed.

For the compensated gap region, the need for a correction depending on the front back energy ratio is not so obvious as seen in Fig. 7. A quadratic correction improved the energy resolution from 1.33 to 1.23% at 90 GeV and was used for all energies.

4.2.2. Dependence of the energy on the electron impact point.

As the impact point of an electron moves transversely to the accordion folds, there is a variation of lead and liquid argon traversed by the shower and thus a variation of the energy response.

Two examples of such a dependence are shown in Figs. 8a and 8b for the opening gap and the compensated gap geometries respectively. A modulation of about $\pm 1.8\%$ total amplitude is observed for both, with a periodicity of a third of a cell. This modulation is also present in the GEANT simulation, with the same periodicity and with an amplitude which is also in good agreement with the data as shown by the crosses in the figure. In the data, the amplitude of the modulation is about a factor 1.8 worse with the cylindrical geometries than with the parallel geometry as shown in Fig. 8a of Ref. 1. As for the parallel geometry, an energy independent correction was applied, using the x position determined from the calorimeter itself.

The energy response also has a small dependence on the position of the impact point in the vertical direction for both types of geometries. The shape and the amplitude of the y modulation is identical to the one already observed with the parallel geometry prototype. The drop of about 1.5% at the cell boundaries is largely due to the incomplete collection of the energy in the 3×3 cell matrix and was corrected.

4.3. Energy measurements

The resolution and linearity of the various areas of the prototype were measured. The energy was calculated by summing the signals of a matrix of 3 times 3 cells in the transverse direction and the two or three compartments in depth. The different weighting of the energy deposited in the two or three compartments and the x and y corrections described in Section 4.2 were included. The energy distribution of 90 GeV electrons is well reproduced by a Gaussian as can be seen in Figs. 9a and 9b for the opening and compensated gap geometries respectively. The tails at low energy represent at most 1% when counted beyond 3σ from the peak.

4.3.1. Energy resolution

The fractional energy resolution from a Gaussian fit is shown in Figs. 10a and 10b as a function of the electron beam energy for the two calorimeter geometries respectively, in the single transistor area for the opening gap and in the zero transistor area for the compensated gap. The resolutions were measured with a beam which spread over the whole cell in x and about half the cell in y.

The variation of the resolution as a function of energy can be fitted by the quadratic sum of a $1/\sqrt{E}$ sampling term, a constant term and a $1/E$ noise term.

The results of the fits of σ_E/E are given in Table 1, together with the results of the parallel geometry prototype. The beam resolution has been unfolded.

Table 1 : Results of fits of σ_E/E for different configurations

			Sampling $\sqrt{(\text{GeV})}$	Constant	Noise (GeV)
compens	As	Ga	$10.0 \pm 0.5\%$	$0.57 \pm 0.05\%$	0.32 ± 0.04
"	0	T	$8.4 \pm 0.8\%$	$0.71 \pm 0.06\%$	0.47 ± 0.05
opening	1	T	$10.7 \pm 0.6\%$	$0.65 \pm 0.06\%$	0.46 ± 0.03
parallel	As	Ga	$9.6 \pm 0.3\%$	$0.32 \pm 0.04\%$	0.33 ± 0.015

The sampling terms, about 10%, are similar for all measurements within the errors.

The constant terms of the cylindrical geometries are about 0.7%. They are a factor about 2 worse than in the parallel geometry. By using the beam telescope, subsamples of data limited to a narrow band of 2 mm in the x direction allow the measurement of the local resolution and the fit as a function of energy resulted in constant terms which were then of the order of 0.3 to 0.4%.

The noise terms are compatible with the values measured from the pedestal fluctuations as reported in Section 3. For the areas readout with the single or the zero

transistor scheme, the signal was not amplified inside the cryostat, and the level of coherent noise was such that it had to be taken into account when summing 18 channels with zero transistor readout and 27 channels with single transistor readout. A substantial reduction of the noise should be achieved in the next test beam period.

4.3.2. Linearity of response

For each beam energy the mean response of the calorimeter was taken as the central value of the Gaussian fit. The gain of the electronic chain and the pedestal variations were regularly monitored during data taking. The ratio of the calorimeter response to the beam energy is shown in Figs. 11a and 11b for the same two regions as in Fig. 10. The result at 90 GeV was used as reference point. A 2% deviation is observed at 20 GeV in the opening gap part. The present data do not allow to attribute the deviation, if real, to the calibration of the single transistor or to non linearity in the calorimeter response at low energy, obtained with fixed weights.

4.3.3. Variation of the response as a function of the angle of incidence

As already discussed in section 4.2.2, the calorimeter response is modulated in the x direction. Since this modulation results from the alignment of absorber corners along the depth of the calorimeter, special data have been taken with the cryostat rotated in the horizontal plane around one central cell of the gallium arsenide area. The x modulation was thus studied at 0, 1.5, 2.2 and 3.5 degrees of angle of incidence. The modulations showed an amplitude of respectively, 1.8%, 1.4%, 0.8% at the first three angle settings and the modulation was strongly reduced at 3.5 degrees incidence. This can be seen in Figs. 12a and 12b where the 0 and 3.5 degrees response for 150 GeV electrons are given.

At this energy, the modulation in x contributes significantly to the resolution. It is 1.7% at 0° and becomes $1.03 \pm 0.04\%$ after the correction as a function of x. These two values have to be compared to 1.14 ± 0.02 obtained at 3.5° incidence (and no x correction).

4.4. Space measurements

Due to the interpenetration of the cells in the x direction, the core of the electromagnetic shower is distributed in at least two towers in this direction. In the y direction the sharing of the shower core between cells varies more strongly with the impact point. The transverse position of the shower was obtained from the centre of gravity of the energy distribution in a matrix of 3×3 cells. The shower direction can be obtained from the position measured in each of the longitudinal samplings.

4.4.1. Measurement of the shower position.

By using the method described above, the shower position was measured in the two halves of the calorimeter. The measured position was then compared to the position of the track from the extrapolation of the beam telescope measurement. In the vertical direction, the calorimeter measurement was not linear as explained in Ref. 1, and a correction was applied. In the horizontal direction, the linearity of the calorimeter measurement was much better. However, the results were obtained with a parallel beam of electrons and not with a beam diverging from the cylinder axis as it will be in the LHC calorimeter, and consequently, the data were restricted to electrons with an impact within the central third of a cell.

For position measurements, only the amount of energy deposited in the front compartments of the 9 towers were used to calculate the centre of gravity. The position resolution was measured over the range of energies from 20 to 200 GeV. The results depend on the electron energy and were parametrized by a quadratic sum of a constant term and a term in $1/\sqrt{E}$, no contribution of the electronic noise was included since it was negligible in this energy range. The contributions of the resolution of the beam telescope extrapolations, estimated at 0.30 mm and 0.48 mm in the x and y directions respectively, were subtracted and the results are the following :

$$\begin{aligned}\sigma_x &= (2.9 \pm 0.2)/\sqrt{E} \oplus 0.21 \pm 0.04 \text{ mm} \\ \sigma_y &= (5.4 \pm 0.2)/\sqrt{E} \oplus 0.0 \pm 0.2 \text{ mm}\end{aligned}$$

for the single transistor region corresponding to the opening gap geometry and

$$\begin{aligned}\sigma_x &= (3.10 \pm 0.3)/\sqrt{E} \oplus 0.32 \pm 0.04 \text{ mm} \\ \sigma_y &= (4.9 \pm 0.2)/\sqrt{E} \oplus 0.0 \pm 0.2 \text{ mm}\end{aligned}$$

for the zero transistor region in the compensated gap geometry.

The comparison of these results with the ones obtained with the parallel geometry shows some differences. In the x direction the resolutions are similar below 100 GeV, but the cylindrical geometries exhibit a constant term of 0.2 to 0.3 mm consistent with longitudinal shower fluctuations, while it is compatible with zero in the parallel geometry. In the y direction the resolution with the cylindrical geometry is as expected very similar to the one achieved with the parallel geometry.

4.4.2. Angular resolution

From the position measurement of the shower in the front and back part of the calorimeter, the shower direction can be estimated provided the lever arm between the two compartments is known. As explained in Ref. 4, the average distance along the shower direction of the two energy centres of gravity need to be calibrated. This can be obtained from the variation of the quantity $x(\text{front}) - x(\text{back})$ as a function of the rotation of the calorimeter around a vertical axis. For the half of the prototype with two samplings, and a separation after 13.4 radiation lengths, the lever arm was 125 mm. For the side with three samplings, and a first separation after 8.6 radiation lengths, the lever arm between the first and the second compartment was 85 mm.

In the part of the prototype equipped with three compartments a study showed that the energy deposited in the third compartment is too small to be used significantly with the front compartment in the direction measurement. It is also not added to the second compartment, since it even spoils the resolution at low energy.

The result of the resolution measurements are shown in Figs. 13a and 13b for both sides. The curves result from the following parametrizations

$$\sigma_{\theta x} = (56 \pm 1) / \sqrt{E} \oplus (180 \pm 30) / E \text{ mrad}$$

for the three sampling calorimeter and

$$\sigma_{\theta x} = (80.2 \pm 2.4) / \sqrt{E} \oplus (64.5 \pm 6.5) / E_{\text{back}} \text{ mrad}$$

for the two sampling calorimeter.

The angular resolution at low energy deteriorates faster than $1/\sqrt{E}$. This was attributed to the electronic noise which affects the measurement of the shower position in the second compartment, especially at low energy where the shower deposits little energy. This worsening of the resolution was particularly important when the second compartment started after 13.4 radiation length. In this case, the resolution was better parametrized if the energy appearing in the $1/E$ term was the energy deposited in the second compartment. The values of the $1/E$ terms are consistent with the measured electronic noise. Achieving a better direction measurement of low energy showers clearly needs a further optimisation of the separation between the two compartments.

5. CONCLUSIONS

A prototype of a liquid argon electromagnetic calorimeter with a cylindrical geometry has been built and tested. Two different types of absorber plates were investigated, for one the argon gap was opening along the depth and for the other it was maintained fixed by a cladding of the absorber with a layer of glass epoxy of increasing thickness.

Three different schemes of front-end readout electronics were tested. In the first, preamplifiers with gallium arsenide were directly mounted on the calorimeter faces. In the last two schemes, a charge preamplifier using bipolar transistors was located outside the cryostat and connected to the calorimeter either directly or through a single common gate transistor.

Both absorber designs lead to similar results. The energy resolutions measured with electrons of energy between 20 and 200 GeV are about $10\%/\sqrt{E}$ (GeV) with a local constant term of about 0.65%. Depending upon the front-end electronics, the noise contribution ranged between 300 and 500 MeV. A modulation of the energy response of a total amplitude of about 3.6%, as a function of the impact point was observed and corrected for.

The accuracy of the shower position measurement is $3.0 \text{ mm}/\sqrt{E}$ (GeV) with a constant term of 0.2 to 0.3 mm in the direction of the folds. The accuracy in the direction parallel to the folds is about a factor 2 larger. The measured angular resolution obtained from the position measurements in two compartments of the calorimeter depends significantly upon where the two compartments are separated. When the separation occurs after 9 radiation length, the resolution is $56 \text{ mrad}/\sqrt{E}$ (GeV) in quadrature with a noise contribution of $180 \text{ mrad}/E$ (GeV).

Due to the short shaping time, the performances obtained with the opening gap geometry are as good as those of the compensated gap and the construction of the absorber plates is much simpler.

A comparison of the energy resolution achieved with these cylindrical geometries to that of the parallel geometry shows that the sampling terms are similar, but the response modulation and the constant terms are a factor 1.5 to 2 worse. The space resolution are also similar at low energy, but the cylindrical geometries exhibit a small constant term.

To reduce the constant terms to the level measured with the parallel geometry, a third prototype will be built and tested in 1992. In this prototype, both the absorber and the argon gap thickness will be maintained constant by varying the bending angle of the folds along the depth of the calorimeter.

The good results obtained with this cylindrical prototype give confidence in the possibility of building a calorimeter for an experiment at LHC.

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Fig. 1 Section of the prototype calorimeter:

- a) The front and the back folds are shown in the left and the right side of the figure. The lower half corresponds to the opening gap and the upper half to the compensated gap geometries, as more visible in the right part of the figure.
- b) detail sketch of the compensated absorber plates.

Fig. 2 Schematic view of the prototype assembly and the four different readout regions.

Fig. 3 Theoretical equivalent noise charge calculated in the readout scheme with the preamplifier located outside the cryostat, as a function of the length of the connection line and for three different peaking times.

Fig. 4 Example of the GEANT simulation of a 90 GeV electron shower in the opening gap prototype. Only the electron tracks with an energy in excess of 10 MeV are shown.

Fig. 5 Example of a liquid argon pulse simulated after a shaping with a time response of 20 ns to delta excitation.

Fig. 6 Variation of the energy response of the opening gap calorimeter normalized to the beam energy for 90 GeV electrons as a function of the ratio of the energy in the front (Fig. a) or the back (Fig. b) compartment to the total. The histograms show the data and the crosses, the GEANT simulation. The dashed lines show the simulation for a full charge integration.

Fig. 7 Variation of the energy response of the compensated gap calorimeter normalized to the beam energy for 90 GeV electrons as a function of the ratio of the energy in the front compartment to the total. The histogram shows the data and the crosses the GEANT simulation.

Fig. 8 Variation of the energy response of the calorimeter normalized to the beam energy for 90 GeV electrons as a function of the impact point in the x direction in cell units. Figure a is for the opening gap and Fig. b for the compensated gap. The histograms show the data and the crosses the GEANT simulation.

Fig. 9 Histograms of the energy response of the opening gap (Fig. a) and the compensated gap (Fig. b) calorimeter to a 90 GeV electron beam.

Fig. 10 Energy resolution as a function of the electron energy for the opening gap (Fig. a) and the compensated gap (Fig. b) calorimeter. The curves represent the fit indicated in the figure, the energy being expressed in GeV.

Fig. 11 Energy response normalized to 1 at 90 GeV showing the linearity of the calorimeter with opening gap (Fig. a) and compensated gap (Fig. b).

Fig. 12 Energy response of the compensated gap calorimeter normalized to the beam energy for 150 GeV electrons as a function of the x impact point in cell units. Figure a is for a beam hitting the calorimeter at normal incidence, and figure b is for an incidence tilted by 3.5° in the horizontal plane.

Fig. 13 Angular resolution measured with the calorimeter as a function of the electron energy. The curves represent parametrisations explained in the text. Figs. a and b correspond to a separation between the two compartments after 8.6 and 13.4 radiation lengths respectively.