PERFORMANCE STUDIES OF LEAD/SCINTILLATING-FIBRE
CALORIMETERS IN THE 1 TO 10 GeV RANGE

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Abstract

Three calorimeter modules made of scintillating fibres embedded in a lead matrix were tested at the CERN Proton Synchrotron. The linearity of the energy response to electron-induced showers, measured in a module having a lead-to-fibre volume ratio of 1.8, is verified within 2.5% whilst the energy resolution is found to be $9.6\%/\sqrt{E} + 1\%$ at 6° and 4° impact angles in the horizontal and vertical planes. An impact position resolution of $1.51 \text{ mm}/\sqrt{E} + 1.45 \text{ mm}$ is achieved. The $e/\pi^\pm$ separation based on the longitudinal and transverse shower size is discussed for various calorimeter configurations. Requiring an energy above a threshold of 3 GeV leads to a $\pi^\pm$ rejection factor of 12 to 36 with a longitudinal criteria, and a $\pi^\pm$ rejection factor of 43 to 100 with a transverse cut in a $\pi^\pm$ energy range of 3 to 7 GeV. A combination of both criteria leads to a rejection factor between 116–303 in the same energy range. The study of the time shape of the signals shows a very small intrinsic jitter of 0.4 ns on the calorimeter signals. It does not show any evidence of a detectable neutronic tail in $\pi^\pm$ signals.

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1. INTRODUCTION

Stringent requirements for calorimeters, such as high compactness, fine granularity, good energy resolution, and rapidity of the signals has led to the development of a new generation of fibre calorimeters in the framework of the Large Hadron Collider (LHC) project. We report here on the performances of lead/fibre calorimeters in view of an upgrade of the backward electromagnetic calorimeter of the H1 experiment at the ep collider HERA at DESY [1].

In H1, the measurement of the outgoing electron from deep inelastic scattering (DIS), with a parton carrying a small fraction of the incident proton momentum, requires good energy resolution (at least $\approx 10\%/\sqrt{E}$) and good electron/pion separation in the 3 to 10 GeV range, where DIS and photoproduction hadronic background go beyond the electron rates by a factor up to 100. Moreover, a calorimeter placed at small scattering angles ($4^\circ < \theta < 30^\circ$) is plagued by additional proton beam collisions with collimators and residual gas in the vacuum pipe, five orders of magnitude in rates (100 kHz) above DIS processes. This last background could be reduced by 3 orders of magnitude using calorimeter time-of-flight measurements included in a first-level trigger. Another 1 to 2 orders of magnitude of reduction could be obtained by pulse-shape discrimination, rejecting pile-up events within the 96 ns period between two beam bunch-crossings. Such time-rejection can be performed only with a very rapid detector based on the few nanosecond scintillation process. Additional π rejection can be obtained by longitudinal and transverse shower size discrimination. A calorimeter based on parallel scintillating fibres embedded in a lead matrix [2] could fit the stringent performance requirements for the H1 backward calorimeter upgrade.

In this paper, the results obtained with three different prototypes, which have been placed in a test beam at the CERN Proton Synchrotron (PS) during July 1992, are presented. Some of these results are compared with those obtained in the CERN Super Proton Synchrotron (SPS) H2 beam. In Section 2, the experimental set-up, the calorimeters, and the calibration procedure are described. Results on energy and position resolutions are presented in Section 3. The electron/charged-pion separation is extensively discussed in Section 4 in view of the shower shape discrimination. Timing properties of the signals are discussed in Section 5.

2. EXPERIMENTAL SET-UP

2.1 The beam line

The calorimeters were tested in the T7-North CERN PS area, where electron and charged-pion beams were available in the 1 to 10 GeV range. The experimental layout is shown in fig. 1.

The calorimeters were installed on a movable table allowing horizontal and vertical displacements and rotation in the horizontal plane. Multiwire drift chambers (*MWC1,2*) equipped with 4 planes of wires for both transverse coordinates provided an impact-point position on the front surface of the calorimeter with a precision of 500 μm .

A trigger was obtained by the coincidence of the signals from several scintillators (*S1* to *S4*) and Cherenkov (*C1, C2*) detectors exposed in the beam line. The trigger elements consisted of:

- the first two large crossed scintillators, about 10 cm wide defining a broad beam;
- the next two narrower crossed scintillators selecting a narrow beam spot of $1 \times 1 \text{ cm}^2$;
- a fifth scintillator with a 5 mm diameter hole (used in anticoincidence), allowing

- precise impact-point selection on the front face of the calorimeter;
- two threshold Cherenkov counters allowing for electron/hadron selection in the beam. The positive hadron beam (hereafter called π^+ beam) contains an admixture of protons [3] that we cannot distinguish from π^+ . The $\pi^\pm$ contamination in the e beam is estimated to be at the few per cent level, whilst the e contamination in the $\pi^\pm$ beam can be neglected.

Pions were absorbed in 1.2 m of concrete downstream of the calorimeters and muons could be detected by a backing scintillation counter (S6).

2.2 The acquisition system

The acquisition system relied on a Motorola 68030 microprocessor that runs the SPIDER acquisition program [4] under the multi-tasking environment of the OS-9 operating system. The microprocessor reads the ADCs (Lecroy 2249) in a CAMAC crate, through a VME bus and a VME/CAMAC Branch-Driver. The data were recorded on Exabyte tapes.

2.3 The calorimeters

Three prototype modules (see fig. 2) were constructed in the framework of the research and development for the LHC at CERN, by the RD1 Collaboration [5]. A detailed description of the mechanical design can be found in ref. [6]. The main features of the three calorimeters are the following :

- The first small prototype (called “A” henceforward) is made of four equal-size towers, each having a $4 \times 4 \text{ cm}^2$ transverse cross-section and 30 cm length. This module consists of lead plates in which grooves have been machined. Polystyrene fibres (Kuraray, dopant 3HF 20 ppm + PTP, cladding 30 μm of PMMA) having 500 μm diameter and emitting green light (they are radiation hard) were inserted in these grooves. Mirrors were put on the front face of the fibre in order to increase the effective light attenuation length. The lead plates were stacked together. The lead-to-fibre volume ratio is 4. This ratio has been prescribed to achieve almost complete compensation [7]. The radiation length X_0 is 7.2 mm, the Moliere radius R_M is 1.5 cm, and the nuclear interaction length λ_{int} is 21cm. The fibres of each tower were bunched together at the rear of the module and connected to a light Plexiglas mixer. The light output was converted into electric signals via Philips XP2961 photomultipliers.
- The second prototype (“B”) is made of four towers, each tower having a $6 \times 6 \text{ cm}^2$ transverse cross-section and 30 cm length. The polystyrene fibres (Kuraray SCSF 38) have a 1 mm diameter and emit blue light. The front faces of these fibres have not been aluminized. Lead plates were extruded and were glued together after the insertion of the fibres. The lead-to-fibre volume ratio is about 1.8. The radiation length X_0 is 8.6 mm, the Moliere radius R_M is 1.7 cm, and the interaction length λ_{int} is 23.8 cm. As for the module “A”, fibres were bunched to feed light mixers at the rear. Philips XP2020 photomultipliers were used for light detection.
- The third prototype “C” has 24 towers of which 20 have a parallelepipedic form of $4 \text{ cm} \times 4 \text{ cm} \times 30 \text{ cm}$ size. The last four towers placed on one side of the calorimeter have a corner shape (for LHC projectivity studies). They have not been used for the analysis of the PS data. This prototype has the same lead to fibre volume ratio as the “B” prototype, hence it has the same X_0 , R_M and λ_{int} . The polystyrene fibres (Kuraray, dopant 3HF 500 ppm + PTP, cladding 30 μm of PMMA) have a 1 mm

diameter and emit green light. Mirrors were put on the front face of the fibres. The lead plates were extruded and then soldered with a low fusion point alloy after the insertion of the fibres. The photomultipliers are Philips XP2962.

2.4 The energy calibration of the towers

Each tower was calibrated individually with a 5 GeV e^+ beam hitting its centre. The high voltages of the photomultipliers were adjusted to get at their anode a gain of 20 pC per GeV. Further calibration was performed off-line by tower response equalization. Static ADC pedestals were measured with a random trigger in special runs, when there was no PS beam, and were subtracted off-line.

3. ELECTROMAGNETIC SHOWER MEASUREMENTS

In this section, we present the performances for the response to electromagnetic showers of the “C” prototype, which has the best transverse shower containment. This calorimeter was installed with a systematic tilt of 6° in the horizontal plane and 4° in the vertical plane with respect to incident beam.

3.1 Energy response

3.1.1 Linearity

The mean signal response measured as a function of the electron beam energy is shown in fig. 3a and the non-linearity, defined as the deviation of the measured energy from a straight line fit to the response curve, is shown in fig. 3b. The maximum non-linearity is 2.5% in the 1 to 7 GeV range. This non-linearity could be due to systematic effects, such as hysteresis effects in the beam magnets, or energy loss in materials in front of the calorimeter.

3.1.2 Resolution

The energy resolutions measured as a function of the incident energy are shown in fig. 4 for the default incident angle of 6° in the horizontal plane and 4° in the vertical plane. The measured points were fitted to functions including a sampling term ($\propto 1/\sqrt{E}$) and a constant term added either linearly or in quadrature. The results are:

$$\begin{cases} \frac{\sigma}{E}(\%) = \left(\frac{9.65 \pm 0.22}{\sqrt{E}} \right) + (0.97 \pm 0.12), & \chi^2/\text{ndf} = 1.32 \\ \left(\frac{\sigma}{E}(\%) \right)^2 = \left(\frac{10.39 \pm 0.15}{\sqrt{E}} \right)^2 + (2.48 \pm .15)^2, & \chi^2/\text{ndf} = 1.85 \end{cases} \quad (1)$$

where E is in GeV. These two functions lead to hardly distinguishable predictions in the 1 to 7 GeV range. This result can be compared with the energy resolution obtained from the SPS beam data:

$$\frac{\sigma}{E}(\%) = \left(\frac{9.23 \pm 0.69}{\sqrt{E}} \right) + (0.38 \pm 0.10), \quad \chi^2/\text{ndf} = 1.15. \quad (2)$$

The sampling terms of eqs. (1) and (2) are compatible within the experimental errors, as expected if these terms arise mainly from sampling fluctuations. The contribution of photoelectron statistics at the photomultiplier photocathode is negligible. The differences in the constant terms between the PS and the SPS data could be partly explained by the different intrinsic beam momentum dispersions.

3.2 Position reconstruction

The mean shower position can be calculated from calorimeter information by a barycentre method. The position resolution is obtained by comparing the shower barycentre to the particle impact-point position provided by the wire chambers. From the calorimeter, we get

$$\bar{u} = \frac{\sum_i u_i E_i}{\sum_i E_i},$$

where E_i is the energy measured in the tower i and u_i is the coordinate of the tower centre along the considered axis (x or y). The reconstructed position is not a linear function of the real shower position x_{ch} measured in the wire chambers. Figure 5 shows the familiar S-shape relation, due to the geometry of the towers, between the estimated and the real positions for 7 GeV electrons. The estimated position can be corrected as follow:

$$\begin{cases} x_{\text{corr}} = (1.11 \pm 0.12) \arctan \{(2.51 \pm 0.07) \bar{x}\} \\ y_{\text{corr}} = (1.23 \pm 0.02) \arctan \{(2.41 \pm 0.06) \bar{y}\} \end{cases} \quad (3)$$

with all coordinates measured in centimetres. Making the differences between the corrected positions x_{corr} and x_{ch} yields a 2 mm position resolution for 7 GeV electrons. The position resolution dependence on the beam energy is shown in fig. 6 and is fitted as:

$$\sigma_x = \left(\frac{1.51}{\sqrt{E}} + 1.45 \right) \text{ mm}.$$

4. ELECTRON/CHARGED-PION SEPARATION

The $e/\pi^\pm$ separation, based on the different shower evolutions and sizes, can be performed in both longitudinal and transverse directions with respect to the shower axis.

Transverse shower sizes can be estimated by the energy-sharing measurement between contiguous cells. For that, we only use the prototype “C” which has the best transverse containment.

A lead/fibre calorimeter does not offer by itself a longitudinal segmentation. The difference in longitudinal shower depth can nevertheless be estimated by using several configurations of the three prototypes as shown in fig. 7. Longitudinal studies are performed by placing the small modules “A” and/or “B” in front of the “C” module, which implies that the fibres of the “A” and/or “B” modules are perpendicular to the beam axis whilst the prototype “C” fibres are parallel to the beam. Hence, three lengths ($11.4 X_0$, $14 X_0$ and $25.4 X_0$) of the first section leading to three very different configurations were studied¹⁾.

The combination of transverse and longitudinal information was studied by putting the two calorimeters “A” and “B” behind the calorimeter “C”, i.e. after $35 X_0$ or $1.3 \lambda_{\text{int}}$.

4.1 Transverse separation

The beam spot is spread over a surface corresponding to about one central calorimeter cell ($3 \times 1 \text{ cm}^2$ as seen from fig. 5) in the transverse configuration. The energy-sharing among cells depends on the particle type (here e or $\pi^\pm$), on its impact-point (x, y), and on

1) The first and third longitudinal configurations do not have the same depth ($2.2 \lambda_{\text{int}}$) as the second configuration ($1.8 \lambda_{\text{int}}$).

the incident angle (θ, ϕ) . The fraction of energy deposited in each cell can be fitted to a function $f_i(r)$ depending on a single parameter r , the distance of the impact-point to the centre of the calorimeter. A function $f_i(r)$ approximated by a fifth-order polynomial, is extracted from electron data at fixed angles $(\theta = 6^\circ, \phi = 4^\circ)$ and 7 GeV incident energy.

The differences in the deposited energy fractions in nine contiguous cells allow for $e/\pi^\pm$ separation. Let us define a transverse size estimator as follows:

$$\mathcal{K}^2 = \sum_{i=1}^{i=9} r_i \left(\frac{E_i}{E_{\text{tot}}} - f_i(r) \right)^2, \quad (4)$$

where E_i is the deposited energy in the cell i , E_{tot} is the total energy deposited in the calorimeter, and r_i is the distance of the impact-point to the i -cell centre. This estimator compares the measured fraction of deposited energy E_i/E_{tot} with the expected $f_i(r)$ one. Energy fraction differences between electrons and charged pions should be mainly detected in lateral shower tails. But both E_i/E_{tot} and $f_i(r)$, as well as their differences, being small in showers tails, we have to weight this difference squared by the r_i parameter approximating the distance of the shower tail to the principal axis of the shower. The $\mathcal{K}^2$ distribution obtained for electrons and pions of 1 to 7 GeV is shown in fig. 8. It must be noted that the $\mathcal{K}^2$ could only be weakly determined for large r values, given the low impact-point density on the middle cell borders. With sufficient constraint at large r , it is hoped that the $e/\pi^\pm$ separation could be made independent of the impact-point position.

4.1.1 Transparency function

The transparency function is defined as the fraction of charged pions which have deposited an energy above a threshold. It is shown in fig. 9, as a function of the threshold for π^+ of 1 to 10 GeV. The study of the transparency functions is motivated by applications in DIS events at HERA, where the scattered electron is selected from a rather flat distribution above an energy threshold of 3 to 5 GeV, high enough to suppress the steeply falling background spectrum of minimum ionizing particles and low-energy hadrons. A tiny difference in energy deposition between positive and negative pions is observed, which is in accordance with nuclear cross-sections, i.e. π^- deposit slightly more energy than π^+ do. In the following, we do not distinguish π^- from π^+ given that the transparency functions are modified in the same way after application of shower-profile cuts.

4.1.2 Effect of a transverse cut on the transparency function

The $\mathcal{K}^2$ cuts have been chosen to allow for a 90% (or 95%) single-electron selection efficiency ϵ_e at any energy. They are derived from fig. 8 and are reported in table 1 according to the mean electron energy. The $\mathcal{K}^2$ cuts applied at each pion event could be calculated in two ways. In the first way, the $\mathcal{K}^2$ cut is chosen to select electrons having the same energy as that of the **incident** pion with $\epsilon_e = 90\%$ (this procedure is hereafter called the method α and the relative cut is $\mathcal{K}_\alpha^2$). But, in practice, the energy of the incident pion is unknown if no momentum measurement is performed. So in the second way, the $\mathcal{K}^2$ cut is chosen to select electrons having the same energy as the **deposited** energy with $\epsilon_e = 90\%$ (this procedure is hereafter called the method β and the relative cut is $\mathcal{K}_\beta^2$). For that case, the $\mathcal{K}^2$ cut was calculated, event by event, by interpolating via a linear fit over the $\mathcal{K}^2$ cut values at 3, 5, and 7 GeV given in table 1.

The method β is seen to be less efficient in the π^+ rejection than the method α because those pions which deposit a small fraction of their incident energy have their

$\mathcal{K}^2$ value compared with a larger $\mathcal{K}^2$ cut. The greater difference at 7 GeV of the $\mathcal{K}_\alpha^2$ cut compared with the $\mathcal{K}_\beta^2$ cut may be partly due to the fact that $f_i(r)$ was calculated for 7 GeV electrons.

Figure 10a shows an example of the transparency function for 5 GeV π^+ before and after having applied transverse cuts. Table 2 gives the π rejection factors obtained by requiring an energy threshold and applying transverse cuts, where the rejection factor is defined as the inverse of the probability of identifying a charged pion as an electron.

Pure transverse cuts (without energy threshold requirement) reject 3 GeV $\pi^\pm$ by a factor of 4.4 (compared to 3 GeV e) and 7 GeV $\pi^\pm$ (compared to 7 GeV e) by a factor of 28. The relative improvement of the $\pi^\pm$ rejection brought about by transverse cuts decreases when there is enough deposited energy. Indeed a larger amount of deposited energy implies a higher electromagnetic energy fraction in the $\pi^\pm$ shower. In the ultimate case, where all the initial energy is visible, the π shower looks like an electron shower. Requiring a minimal energy of 3 GeV in addition to the transverse $\mathcal{K}_\alpha^2$ cut leads to a rejection factor above 40 (instead of 4 with no transverse cut) for $\pi^\pm$ between 1 and 7 GeV. Increasing the threshold to 5 GeV leads to a rejection factor above 150 (instead of 20 with no transverse cut) for $\pi^\pm$ in the same energy range.

4.2 Longitudinal separation

The longitudinal configurations consist of two separated sections along the beam axis. We define the longitudinal estimator R_L as follows:

$$R_L = \frac{\text{Energy in the section downstream}}{\text{Energy in the section upstream}} \quad (5)$$

Figure 11 shows an example of R_L distributions for electrons and pions at 5 GeV.

4.2.1 Longitudinal configurations 1 and 2

In configuration 1, the first section length is $14 X_0$, and the total calorimeter length is $49 X_0$ or $1.8 \lambda_{\text{int}}$. For electron energies of 5, 7, and 10 GeV, the R_L cuts are given for electron-selection efficiencies $\epsilon_e = 90\%$ and $\epsilon_e = 95\%$ in table 3.

In the configurations 2, there are two possible lengths of the first section: a first section length of $11.4 X_0$ in configuration 2a and a first section length of $25.4 X_0$ in configuration 2b. The total length of the calorimeter is $60.4 X_0$ or $2.2 \lambda_{\text{int}}$.

The R_L cut is given in table 4 for electron energies of 1, 3, 5, and 7 GeV at $\epsilon_e = 90\%$ and $\epsilon_e = 95\%$.

4.2.2 Transparency functions and rejection factors

The effect of the longitudinal cut on the transparency function is shown in fig. 10b for the configuration 1. Similar functions are obtained for the configurations 2.

As in section 4.1.2, the R_L cut is calculated according to two methods. Contrary to the transverse configuration case, the method β is almost as efficient with respect to pion rejection, but the difference in that rejection is smaller. With that method, it is easier to distinguish longitudinally a pion from an electron shower when a small fraction of its energy is deposited early whilst, conversely, a low deposited energy is harder to distinguish transversely from a low-energy electron.

The π^+ rejection factors obtained with and without R_L cuts above various energy thresholds are summarized in tables 5 and 6. Without an energy threshold requirement,

the rejection factors are larger when the calorimeter is longer. This is due to the fact that a $\pi^\pm$ has more chance of undergoing a hadronic interaction in a long calorimeter than in a short calorimeter, especially at high energies. For instance, in the energy range of 5 to 7 GeV, the rejection factors (obtained with the method α) are around 4–5 for the configuration 1 and they are around 6–8 for the configurations 2. Applying an energy cut of 3 GeV shows that the rejection factors are the largest in the configuration 1 for the 5–7 GeV range.

Indeed the energy requirement selects those $\pi^\pm$ which have performed a hadronic interaction and developed a hadronic shower with substantial containment. As it is crucial to reject those pions which deposit much energy, from the rejection factors number we deduce that the configuration 1 has the optimal first-section length ($14 X_0$) to separate e from π in the 5–7 GeV range. This rejection factor goes from 36 at 5 GeV to 12 at 10 GeV. Comparing the rejection factors obtained with the configurations 2a and 2b shows that a $11.4 X_0$ first-section length is better for e/π separation in the 3–5 GeV range, whilst a $25.4 X_0$ first-section length is better for e/π separation in the 7–10 GeV range.

4.3 Combined separation

The combination of the longitudinal and transverse criteria has been studied with the tail-catcher configuration (see fig. 7d). Figures 12a and 12b show the scatter plot of the energy in the tail-catcher and the energy in the front calorimeter for electrons and pions at 5 GeV. As for the longitudinal study, we define the longitudinal estimator as follows:

$$f_{\text{out}} \equiv \frac{\text{Energy in the tail catcher}}{\text{Energy in the calorimeter}} \quad (6)$$

The correlation between the longitudinal estimator and transverse estimator ($\mathcal{K}^2$) are shown in figs. 12c and 12d. Cuts on the longitudinal parameter are chosen from f_{out} projection distributions as shown in fig. 13. The resulting single-electron selection efficiencies are given in table 7.

The effect on the transparency function of the combined cuts is seen in fig. 10c. Again the cuts were applied for the two methods described in section 4.1.2. In the method β , the f_{out} cut was calculated from a linear fit over its values at 3, 5, and 7 GeV given in table 7. The method β is less efficient in the pion rejection than the method α for the same reason as quoted in section 4.1.2.

The f_{out} cut brings an additional factor of 10 to the π rejection compared to the transverse cut alone (see tables 2 and 8). It has no effect for π which have most of their incident energy detected. Requiring a minimal energy threshold of 3 GeV leads to a rejection factor of 116 at 3 GeV, 179 at 5 GeV, and 303 at 7 GeV. Note that the first-section length in that case is not optimized and could be tuned for a better rejection.

4.4 Conclusion on $e/\pi^\pm$ separation

The longitudinal analysis gives an optimal first-section length for $e/\pi^\pm$ separation of 15–20 X_0 in the 5–7 GeV range. Without a minimal measured energy requirement, using the method α , the longitudinal criteria gives a π rejection factor of about 4–5 in the 5–10 GeV range. The transverse criterion gives a π rejection factor of 4.4 to 28 in the 3–7 GeV range. But the electrons in deep inelastic events at HERA will be selected above

a fixed energy threshold. Choosing a threshold of 3 GeV leads to a rejection factor of 12–36 with longitudinal estimators, a rejection factor of 43–100 with transverse estimators, and a rejection factor of 116–220 in the combined analysis.

5. TIMING OF THE SIGNALS

5.1 Time response

We consider here the time structure of the response to 5 GeV electrons and pions impinging on calorimeter “A”. In special runs, a digital scope (Tektronix DSA 602A) had its four analog inputs connected to the four photomultipliers’ anodes through cables of 10 m length. Each channel was sampled at a 500 MHz frequency and the sampling of one channel after the other was shifted by 0.5 ns. Figure 14 shows the time patterns measured on the four analog inputs. The analysis was performed by summing off-line the signals of the four channels. Figure 15a shows the event by event pulse shape of electrons. The mean rise time (from 10% to 90% of the maximum amplitude) is 4 ns and the mean decay time (obtained from an exponential fit on the mean pulse tail beyond the maximum amplitude) is 11 ns. The time profile is similar for all channels whatever the deposited energy fraction. About 97% of the total energy is collected within 40 ns.

The overall amplitudes of the time samples vary from one event to another owing to the finite energy resolution of the calorimeter. The amplitudes on a given time sample are correlated for the two hottest adjacent channels (channels 1 and 2 containing respectively 90% and 10% of the total signal energy), as seen in fig. 15b for the time-sample 2 and fig. 15c for the time-sample 3.

The amplitude dispersion can be translated into time spread using a linear time amplitude relation (i.e. in fig. 15a, we connect the time-sample 2 and the time-sample 3 by a straight line). The time spread of one sample on the front rise is 0.8 ns. This spread includes some contribution from the scope trigger jitter owing to the event by event amplitude fluctuations. This contribution can be eliminated by rather considering the difference in time measurements of the two hottest adjacent channels (see fig. 16). Thus we are left with an intrinsic signal jitter of 0.4 ns.

5.2 e/π separation

One of the purposes of time structure studies was to attempt to detect the late neutrons generated in the hadronic shower signal tail. For that, the scope trigger selected only those pions which deposited sufficient energy in the calorimeter. The threshold was set equivalent to $\simeq 2.5$ GeV for 7 GeV incident pions. Electrons and pions in fig. 17 show a similar timing shape. The fraction of the energy in the tail has been evaluated in the 40 to 60 ns interval and above 120 ns, avoiding reflection signals produced by a small residual cable impedance mismatch. No neutronic energy (see fig. 18) can be distinguished in π signals: the energy fractions in tails for electrons and pions have their means compatible; they only differ in their widths owing to a larger relative electronic noise in the smaller pion signals. This result seems to be in contradiction with the SPACAL Collaboration claim [2] that e/π separation can be achieved with timing. This could be explained by the fact that we use a short calorimeter ($1.32 \lambda_{\text{int}}$) in the present analysis whilst the SPACAL Collaboration used a $10 \lambda_{\text{int}}$ hadronic calorimeter. Thus we conclude that no e/π separation can be performed by timing discrimination in a short electromagnetic calorimeter.

6. CONCLUSION

A fine sampling electromagnetic calorimeter made of 1 mm diameter fibres embedded in lead has been tested in an energy range of 1 to 10 GeV.

Its non-linearity in this energy range is of the order of 2.5%. The energy resolution is 9.6% with a constant term less than 1%. The position resolution is of the order of 2 mm for 7 GeV electrons.

Excellent charged-pion rejection factors were obtained, requiring a deposited energy threshold above 3 GeV and combining longitudinal and transverse shower-shape constraints. Rejection factors above 100 were typically found using two longitudinal segmentations and a fine transverse granularity of the calorimeter. No electron/charged-pion separation power was obtained by using the time-shape measurement of the signals.

Good timing properties offer the possibility of using this calorimeter for trigger purposes. A jitter of 0.4 ns on the signals allows time-of-flight measurement.

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REFERENCES

- [1] H1 Collaboration, Letter of Intent to upgrade the backward region of the H1 detector, DESY PRC 92/03 and H1 internal note 09/92-243;
H1 Collaboration, Technical Proposal to upgrade the backward region of the H1 detector, DESY PRC 93/02.
- [2] D. Acosta et al., Nucl. Instrum. Methods **A294** (1990) 193; *ibid* **A320** (1992) 128, and references therein.
- [3] D.J. Simon et al., Secondary beams for tests in the PS east experimental area, PS/PA/EP/NOTE 88-26 and DJS/gm - 8.8.1988.
- [4] Y. Perrin, Spider User's Guide, CERN (unpublished).
- [5] J. Badier et al., RD1 Collaboration, Test results of an electromagnetic calorimeter with 0.5 mm scintillating fibres readout, preprint CERN-PPE/93-20, submitted to Nucl. Instrum. Methods;
J. Badier et al., RD1 Collaboration, Test results of a fully projective lead scintillating-fibre calorimeter, preprint CERN-PPE/93-21, submitted to Nucl. Instrum. Methods.
- [6] D. Imbault et al, Réalisation de modules électromagnétiques plomb-fibres scintillantes, LPNHE Paris preprint 92/12.
- [7] F.G. Hartjes and R. Wigmans, Nucl. Instrum. Methods **A277** (1989) 379.

Table 1: $\mathcal{K}^2$ cut for single-electron selection efficiencies ϵ_e of 90% or 95% at mean electron energies of 1, 3, 5, and 7 GeV.

Electron energy (GeV)	$\mathcal{K}^2$ cut (cm)	
	$\epsilon_e=90\%$	$\epsilon_e=95\%$
1	0.64	1.00
3	0.14	0.21
5	0.08	0.18
7	0.045	0.09

Table 2: Pion rejection factors with or without transverse $\mathcal{K}^2$ cuts for various energy thresholds. The $\mathcal{K}_\alpha^2$ cuts are fixed according to the method α . The $\mathcal{K}_\beta^2$ cuts are chosen according to the method β (see text).

π^+ energy (GeV)		Energy threshold				
		$E > 0$ GeV	$E > 1$ GeV	$E > 3$ GeV	$E > 5$ GeV	$E > 7$ GeV
1	no cut	1.0 ± 0.05	1.1 ± 0.06	> 2000	> 2000	> 2000
	with $\mathcal{K}_\alpha^2$ cut	1.6 ± 0.09	1.7 ± 0.1	"	"	"
3	no cut	1.0 ± 0.04	1.6 ± 0.08	50 ± 6.6	> 3000	> 3000
	with $\mathcal{K}_\alpha^2$ cut	4.4 ± 0.3	6 ± 0.4	100 ± 22	"	"
	with $\mathcal{K}_\beta^2$ cut	3.6 ± 0.2	5.1 ± 0.3	100 ± 22	"	"
5	no cut	1.0 ± 0.03	1.5 ± 0.02	5.3 ± 0.2	115 ± 19	> 5000
	with $\mathcal{K}_\alpha^2$ cut	9.3 ± 0.5	12 ± 0.8	43 ± 4.6	555 ± 20	"
	with $\mathcal{K}_\beta^2$ cut	4.5 ± 0.2	7.8 ± 0.4	29 ± 3	555 ± 20	"
7	no cut	1.0 ± 0.03	1.6 ± 0.06	2.7 ± 0.1	21 ± 1.2	192 ± 41
	with $\mathcal{K}_\alpha^2$ cut	28 ± 3	32 ± 3	50 ± 6	152 ± 29	800 ± 34
	with $\mathcal{K}_\beta^2$ cut	5.2 ± 0.2	6.7 ± 0.3	13 ± 0.8	110 ± 18	800 ± 34

Table 3: R_L cut for single-electron selection efficiencies ϵ_e of 90% or 95% at mean electron energies of 5, 7, and 10 GeV for the longitudinal configuration 1.

Electron energy (GeV)	R_L cut	
	$\epsilon_e=90\%$	$\epsilon_e=95\%$
5	0.23	0.34
7	0.28	0.43
10	0.44	0.7

Table 4: R_L cut for single-electron selection efficiencies ϵ_e of 90% or 95% at mean electron energies of 1 to 7 GeV for the longitudinal configurations 2a and 2b.

Electron energy (GeV)	Config. 2a		Config. 2b	
	$\epsilon_e=90\%$	$\epsilon_e=95\%$	$\epsilon_e=90\%$	$\epsilon_e=95\%$
1	0.35	0.5	0.06	0.08
3	0.38	0.5	0.028	0.036
5	0.45	0.65	0.030	0.05
7	0.62	0.85	0.036	0.068

Table 5: Pion rejection factors from longitudinal configuration 1 (first-section length $\equiv 14. X_0$). The R_L cut is fixed (see text) according either to the method α (R_L^α cut), or to the method β (R_L^β cut).

π^+ energy (GeV)		Energy threshold				
		$E > 0$ GeV	$E > 1$ GeV	$E > 3$ GeV	$E > 5$ GeV	$E > 7$ GeV
5	no cut	1.0 ± 0.03	1.6 ± 0.04	8.5 ± 0.4	100 ± 14	1667 ± 875
	with R_L^α cut	5.0 ± 0.2	7.5 ± 0.3	36 ± 3	244 ± 51	5000 ± 450
	with R_L^β cut	5.7 ± 0.2	9.1 ± 0.5	39 ± 4	244 ± 51	5000 ± 450
7	no cut	1.0 ± 0.02	1.3 ± 0.03	3 ± 0.1	16 ± 1	100 ± 13
	with R_L^α cut	4.4 ± 0.2	6.7 ± 0.3	15 ± 1	83 ± 10	500 ± 14
	with R_L^β cut	5.7 ± 0.2	8.8 ± 0.4	18 ± 1	89 ± 11	500 ± 14
10	no cut	1.0 ± 0.02	1.5 ± 0.04	2.7 ± 0.1	7.7 ± 0.3	35 ± 3
	with R_L^α cut	4.1 ± 0.1	6 ± 0.2	12 ± 0.6	35 ± 3	175 ± 29
	with R_L^β cut	6.1 ± 0.2	9.7 ± 0.5	19 ± 1	53 ± 5	196 ± 34

Table 6: Pion rejection factors from longitudinal configurations 2a and 2b (R_L^{2a} and R_L^{2b} cuts respectively). The cut on R_L is chosen to select electrons which have the same energy as the considered pions, with a 90% efficiency (without considering any energy threshold).

π^+ energy (GeV)		Energy threshold				
		$E > 0$ GeV	$E > 1$ GeV	$E > 3$ GeV	$E > 5$ GeV	$E > 7$ GeV
3	no cut	1.0 ± 0.02	1.5 ± 0.04	58 ± 5.3	373 ± 81	> 1000
	with R_L^{2a} cut	4.8 ± 0.2	7.0 ± 0.3	215 ± 36	720 ± 215	"
	with R_L^{2b} cut	2.9 ± 0.08	4.0 ± 0.1	162 ± 24	324 ± 66	"
5	no cut	1.0 ± 0.02	1.2 ± 0.03	3.3 ± 0.1	50 ± 4.3	316 ± 63
	with R_L^{2a} cut	6.3 ± 0.2	7.0 ± 0.3	25 ± 1.6	224 ± 38	1000 ± 345
	with R_L^{2b} cut	6.3 ± 0.2	2.6 ± 0.07	17 ± 0.9	160 ± 23	> 1000
7	no cut	1.0 ± 0.02	1.2 ± 0.03	1.7 ± 0.04	7.7 ± 0.3	49 ± 4
	with R_L^{2a} cut	6.3 ± 0.2	7.0 ± 0.3	10.5 ± 0.5	66 ± 6	205 ± 32
	with R_L^{2b} cut	8.3 ± 0.3	8.6 ± 0.4	12 ± 0.6	60 ± 5.4	460 ± 106
10	no cut	1.0 ± 0.02	1.1 ± 0.02	1.7 ± 0.04	3.2 ± 0.09	13 ± 0.6
	with R_L^{2a} cut	7.8 ± 0.3	9.5 ± 0.4	14.5 ± 0.7	42 ± 3.2	200 ± 31
	with R_L^{2b} cut	12.5 ± 0.6	14.5 ± 0.7	19 ± 1	53 ± 4.5	211 ± 34

Table 7: Chosen longitudinal parameter cut for the tail-catcher configuration and resulting single-electron efficiency at 3, 5, and 7 GeV.

Electron energy (GeV)	f_{out} cut	Electron efficiency	
		Only transverse cut	Both cuts
3	0.024	89.6	85.4
5	0.016	88.5	87.5
7	0.012	90.5	88.1

Table 8: Pion rejection factors with combined transverse and longitudinal cuts. The cuts are fixed according either to the method α (first line in the table) or to the method β (second line in the table).

π^+ energy (GeV)	Energy threshold				
	$E > 0$ GeV	$E > 1$ GeV	$E > 3$ GeV	$E > 5$ GeV	$E > 7$ GeV
3	63 $\pm$ 11	63 $\pm$ 11	116 $\pm$ 27	> 3000	> 3000
	59 $\pm$ 10	59 $\pm$ 10	116 $\pm$ 27	"	"
5	167 $\pm$ 34	167 $\pm$ 34	179 $\pm$ 37	714 $\pm$ 290	> 5000
	33 $\pm$ 3	33 $\pm$ 3	50 $\pm$ 6	714 $\pm$ 290	"
7	303 $\pm$ 81	303 $\pm$ 81	303 $\pm$ 81	333 $\pm$ 93	909 $\pm$ 409
	19 $\pm$ 2	19 $\pm$ 2	23 $\pm$ 2	182 $\pm$ 38	1667 $\pm$ 1000

Figure 1: Schematic view of the experimental set-up (not to scale).

Prototype A

Prototype B

Prototype C

Figure 2: Layout of the three prototype calorimeters used for this analysis.

Figure 3: Linearity: (a) output signal as a function of the beam energy and (b) deviation to the fitted straight line as a function of beam energy. (Statistical errors bars are smaller than the size of the points).

Figure 4: Energy resolution as a function of the beam energy for an impact angle of 6° in the horizontal plane and 4° in the vertical plane (resolution at the PS and the SPS are compared, the error bars are smaller than the size of the points).

Figure 5: Position measured in the beam chambers as a function of barycentre estimator in the calorimeter: (a) along the horizontal direction $\theta = 6^\circ$, (b) along the vertical direction $\phi = 4^\circ$. The fitted arctan curves are superimposed on the distributions.

Figure 6: (a) Position resolution as a function of incident electron beam energy. This resolution includes the intrinsic resolution of the beam chambers. (b) Position resolution for 7 GeV electrons.

Figure 7: Configurations made with the three prototypes to obtain transverse and longitudinal segmentations: (a) transverse configuration (the “C” prototype alone), (b) longitudinal configuration 1 (the “B” prototype put transversely in front of the “C” prototype), (c) longitudinal configuration 2 (same configuration as the second one but in addition the “A” prototype is put transversely at the front), (d) tail-catcher configuration (the “A” and “B” calorimeters are behind the “C” one).

Figure 8: Transverse parameter K^2 distribution for electrons and pions of (a) 1 GeV, (b) 3 GeV, (c) 5 GeV, and (d) 7 GeV.

Figure 9: Transparency function for a $2.2\lambda_{\text{int}}$ calorimeter depth obtained with pions of 1 to 10 GeV.

Figure 10: Transparency function for 5 GeV pions before and after applying (a) the transverse cuts, (b) the longitudinal cuts for the configuration 1, and (c) the combined cuts. The full line corresponds to the transparency function when no shower-size cut is applied; the dashed line corresponds to the shower-size cuts chosen in order to have a 90% selection efficiency for electrons with the same energy as the incident pion energy and the dotted line corresponds to shower-size cuts chosen in order to have a 90% selection efficiency for electrons with the same energy as the deposited pion energy. Similar curves have been obtained at other energies and in the other configurations.

Figure 11: Longitudinal parameter distribution for 7 GeV electrons and pions in configuration 2a. Similar distributions have been obtained at other energies and in the other longitudinal configurations.

Figure 12: Energy in the tail-catcher as a function of the energy in the calorimeter for 5 GeV (a) electrons and (b) pions. Longitudinal parameter f_{out} as a function of the transverse parameter K^2 for 5 GeV (c) electrons and (d) pions. Similar distributions were obtained at other energies.

Figure 13: Longitudinal parameter f_{out} distributions for electrons and pions at 5 GeV. Similar distributions were obtained at 3 and 7 GeV.

Figure 14: Time patterns measured on the four analog inputs (a) to (d) used for the analysis, in 2 ns units.

Figure 15: (a) Electron pulse shape in 2 ns units. Sample amplitudes “ a_i ” are normalized to the signal energy “ $\sum a_i$ ” (i is the sample number, each i increment corresponds to a 2 ns time increment). The amplitude sample correlation between two adjacent calorimeter cells: (b) for sample 2, (c) for sample 3.

Figure 16: Time difference between two calorimeter cells in 2 ns units. From this distribution we get a signal jitter of 0.4 ns.

Figure 17: Example of (a) electron time shape and (b) pion time shape, both in 2 ns units. An exponential curve is fitted on the decaying part of the signals to show hypothetical additional apparent energy in the pion signal tail.

Figure 18: Energy fraction in signal tails for 7 GeV electrons and pions in per cent. (a) Fraction of energy in tail between 40 ns and 100 ns for electrons, (b) fraction of energy in tail after 120 ns for electrons, (c) and (d) the corresponding distributions for pions.