PERFORMANCE OF A HIGHLY SEGMENTED SCI.FI.
E.M. CALORIMETER

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ABSTRACT

A prototype of sci.fi. e.m. calorimeter has been constructed in Rome and tested with
2.4 and 8 GeV electron beams at the CERN PS. Each calorimeter module consists of a Bi-
Pb-Sn alloy and scintillating fibres. The fibres are parallel to the modules longer axis, and
nearly parallel to the incident electrons direction; the module cross area is 8 X 24 mm².
Results on energy resolution and impact point space resolution are obtained. Preliminary
results on two e.m. showers spatial separability are also presented.

(To be submitted to Nuclear Instruments and Methods in Physics Research)

* In partial fulfilment of their doctoral thesis.
1 - INTRODUCTION

The main purpose of the R&D program in e.m. calorimetry carried on by our group is to optimize a sc.i.fl. calorimeter structure for what concerns the single-shower impact point precision and the multi-showers resolution [1]. These features are of great interest for the e.m. calorimetry at future very high energy accelerators.

A modular calorimeter prototype has been constructed in Rome and tested at the electron beam T7 of the CERN PS at the end of 1992. This detector has been designed as an improved version of the calorimeter already used in the LEP-5 experiment in 1990/91 [2,3].

2 - THE CALORIMETER

The calorimeter modules are made of a high density alloy (52.5% Bi + 32.0% Pb + 15.5% Sn, in weight) and scintillating fibres of 1 mm diameter, parallel to the module longer axis, and at a small angle to the incident electrons. The filling factor (= fibres volume/total volume) is 19.5 %, and the module length is 35 cm corresponding to 33 R.L.

In the central region, as can be seen in the sketch of Fig.1, each module is divided into three 8 x 24 mm² submodules. This structure is not mechanical but only optical and is obtained by sending three separate fibre bundles to three different PMT's. In this way an 8 mm granularity can be achieved in the x (horizontal) coordinate.

The calorimeter main features are summarized in Tab.1

The alloy melting point is 96 °C. This allows to employ a simple fusion technique. 144 stainless steel tubes (1.1 mm internal, 1.5 mm external diameter) are held in position by two steel plates at the extremities of an aluminium cast. Then the liquefied alloy is poured inside the cast. This technique allowed us to achieve a more satisfactory mechanical precision in the modules, with respect to a 'pure lead' fusion technique previously employed [3], due to the alloy low melting temperature.

Each fibre bundle (48 fibres in a central module, 144 fibres in a peripheral module) is glued to a light pipe. The pipe square cross area has been optimized in order to get a uniform light collection over the whole fibre bundle.

A yellow optical filter is interposed between the light pipe and the PMT in order to improve the attenuation length of the scintillating fibres with a tolerable loss in the total light collection.

The PMT outputs are sent to fast 11 bits 16 channels ADC's (LeCroy 4300B/610 FERA).

3 - TEST AND RESULTS

A first test has been performed in december 1991 at the CERN PS on the T7-South beam with electrons of 2.4 and 8 GeV energy. The detector was placed on a movable platform allowing the horizontal scan of the beam (see Fig.1), as well as a vertical tilt with respect to the beam.

The actual beam horizontal size was reduced to less than 1 mm by gating the calorimeter signals with the coincidence of two crossed scintillation counters; the horizontal one is 5 mm high and the vertical one is a single 1 mm diameter fibre. Furthermore a telescope of two beam chambers 2 meters spaced has been used to measure the direction of the incident electrons; their spatial accuracy is of the order of 0.2 mm. The calorimeter was mainly operated at a vertical tilt angle of 2.5° respect to the electron beam (this value is not optimized).
3a - Energy resolution

The calorimeter energy response turns out to be linear within 2% in the explored energy range, as shown in Fig.2.

The energy resolution $\sigma/E$ is a linear function of $1/\sqrt{(E(\text{GeV}))}$. In Fig.3 the results are presented at 0° and 2.5° vertical tilt angle. They are comparable, but resolutions at 0° are larger probably due to electron channeling. By fitting the data we get:

\[
\begin{align*}
0^\circ &: \quad \sigma/E = 18.5 \text{ \%}/\sqrt{(E(\text{GeV}))} + 1.9 \text{ \%} \\
2.5^\circ &: \quad \sigma/E = 16.0 \text{ \%}/\sqrt{(E(\text{GeV}))} + 1.6 \text{ \%}.
\end{align*}
\]

In a special run at 4 GeV with 2.5° tilt the calorimeter signal was gated with a 'short' pulse. Under these conditions the ADC integrates essentially the first 5 ns of the signal, corresponding to the pulse rise time (Notice that this rise-time is mainly determined by the PMT itself and would be shorter with a faster PMT). The energy resolution turns out to be worse by about 30%.

In Fig.4 the calorimeter response uniformity is shown at 8 GeV. A horizontal scanning through four adjacent modules was done as shown in Fig.1. At the axis origin a small disuniformity (7%) is visible between two modules which are 'mechanically' separated, due to residual mechanical imperfections. No similar effect is seen between modules only 'optically' separated.

We notice that in our highly segmented prototype-calorimeter energy linearity and resolution are not worsened with respect to the performance of less segmented lead-fibres calorimeters [4]. We conclude that residual mechanical imperfections, not uniform light collection from fibres bundles to PMTs, intercalibration of the many modules collecting the energy of a shower, and reduced photoelectron statistics due to the small number of fibres per module (and furthermore to the optical filter) do not affect the overall energy response of this calorimeter.

3b - Spatial resolution

The horizontal position $x$ of an electron showersing in the calorimeter can be determined in a simple way by the centre of gravity $<x>$ of the energy deposited in the various modules. The results are given in Figs.5a and 6a where the $x$-coordinate is measured with the beam chambers. The waving behaviour of these data distributions is typical of the modular calorimeters.

However better results are obtained using a special algorithm as shown in Figs.5b and 6b. The method was derived in the following way. Under the approximation that the transverse energy distribution of a shower can be represented by a two-dimensional gaussian function, the behaviour of $<x>$ as a function of $x$ can be described by a function of $x$ which contains as a free parameter only the width of the gaussian itself. By fitting the data with this function the parameter is fixed. By inverting the function a better estimate $<x>_c$ for $x$ is obtained. The fitted gaussian width does not depend on energy in the explored range.

The precision in reconstructing the impact point of the electronic shower in the horizontal $x$-coordinate is illustrated by Fig.7 at 8 GeV. Here the event's distribution is plotted versus the difference between calorimeter-reconstructed and beam chambers measured $x$-coordinate.

By fitting the experimental data with a gaussian function, $\sigma_x$ is evaluated at various electron energies.

Moreover the algorithm is such that the spatial resolution is quasi-independent on the impact $x$-coordinate.
Both small (8 x 24 mm$^2$) and large (24 x 24 mm$^2$) module space resolution in horizontal coordinate has been analysed.

As shown in Fig. 8, $\sigma_x$ turns out to be a linear function of $1/\sqrt{E(\text{GeV})}$. Experimental points are obtained analysing the data with the algorithm previously described. The beam chamber contribution to the error is not subtracted. We obtain:

$$\sigma_x = 2.8 \text{ mm} / \sqrt{E(\text{GeV})} + 0.07 \text{ mm} \ , \text{ for small modules}$$
$$\sigma_x = 2.7 \text{ mm} / \sqrt{E(\text{GeV})} + 0.6 \text{ mm} \ , \text{ for large modules}.$$  

For the small modules the energy independent term is compatible with the beam chambers resolution. For the large modules the constant term is due mainly to a residual wandering behaviour of the reconstructed $<x>_{c}$ coordinate.

The special 'short gate' run at 4 GeV (see Sect.3a) shows that the spatial resolution is not worsened by gating the 5 ns rise-time of the calorimeter signal.

3c - Spatial separability

As an example of spatial separability between e.m. showers of the same energy and simultaneously detected by the calorimeter, we can compare the spatial distribution of the energy deposited: (i) by a single 8 GeV electron event; (ii) by summing up the contribution of two 4 GeV electron events at a variable distance from each other. (As it could be the case of $\gamma$ separability in the decay $\pi^0 \rightarrow \gamma + \gamma$.) The 8 GeV electron as well as one of the two 4 GeV electrons is always made to impinge in the centre of a module. The second electron impact point is put at variable distances from the first along the x-axis, beginning at 12 mm and decreasing this distance in 2 mm steps. We define now a parameter which depends on the energy deposited in the various modules in the following way: $R = (\text{sum of the signals of all modules not containing the maximum}) / (\text{maximum signal})$.

A distribution of events versus the parameter $R$ is given in Fig.9 where the first histogram refers to a single 8 GeV electron and the second one is obtained by summing up the signals of two 4 GeV electrons. In this example the horizontal separation between the two shower axes is $\Delta = 10 \text{ mm}$. A fraction of single-shower events may be confused with a two-shower and so may be lost. Vice versa a two-shower event may be confused with a single-shower when the horizontal separation $\Delta$ between their axes is small.

In Fig.10 the recognized fraction of the two shower events $F$ is plotted as a function of $\Delta$ for three single e.m. shower losses. The result for two different horizontal segmentation of the calorimeter 8 mm and 24 mm is given in Fig.10a and Fig.10b respectively. The larger segmentation is obtained adding the signal from three adjacent modules.

A balanced situation 'contamination = loss' is fulfilled at 2%, 5% and 10% level with a minimum separation of about 11.5, 9 and 8.5 mm respectively, with the 24 mm segmentation. A better result is obtained with the 8 mm segmentation: the minimum separation occurs at about 10, 7 and 6.5 mm.

4- CONCLUSIONS

We have constructed a modular e.m. calorimeter and performed a preliminary test with electrons from 2 to 8 GeV energy. The main purpose was to improve the spatial resolution i.e. the impact point reconstruction of a single e.m. shower, and the separation of many e.m. showers. A module cross area is 8 (horizontal) x 24 (vertical) mm$^2$. 
The calorimeter was operated at a vertical tilt angle of 2.5° with respect to the electron beam. The energy resolution turns out to be: $\sigma/E = 16.0\% / \sqrt{(E \text{ (GeV)})} + 1.6\%$. The impact point horizontal resolution is: $\sigma_x = 2.8 \text{ mm} / \sqrt{(E \text{ (GeV)})} + 0.07 \text{ mm}$ and $\sigma_y = 2.7 \text{ mm} / \sqrt{(E \text{ (GeV)})} + 0.6 \text{ mm}$ for a module horizontal size of 8 mm and 24 mm respectively. The spatial resolution does not depend on the impact point of the shower, when an appropriate algorithm is utilized in reconstructing the impact position of the electron.

Furthermore it is interesting that gating the calorimeter signal only during the pulse risetime, the energy resolution $\sigma/E$ is worsened (about 30%), while the spatial resolution $\sigma_x$ is unaffected.

Finally an example of spatial separability between 4 GeV e.m. showers indicates that separation better than 10 mm should be achieved by a segmented calorimeter with a module size from 8 to 24 mm. However we have planned further investigations on this subject.

ACKNOWLEDGMENTS

We recall that the fusion technique employed in the mechanical construction of the modules has been developed in Rome with the skilful contribution of L. Andreanelli, F. Bronzini and R. Simonetti.

We warmly thank R. De Salvo for the many useful discussions and suggestions.

We are indebted to A. Contin and R. De Salvo for providing us the telescope of wire chamber during our test run.

We thank K. Batzner for helping us in the T7 beam optimization.

REFERENCES

[1] R&D experiment F1B has been supported by I.N.F.N. in 1991 and 1992.
[3] M. Bertino et al., 5th Pisa Meeting on Advanced Detectors,
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<td>calorimeter total length</td>
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FIGURE CAPTIONS

1 - Sketch of the calorimeter front view; the highly segmented central region 8 mm (horizontal) x 24 mm (vertical) is shown. The hatched area corresponds to scanned horizontal range.

2 - Measured energy versus beam energy with a vertical tilt angle of 2.5°; the energy response is linear within ±2 %.

3 - Energy resolution \( \sigma/E \) turns out to be a linear function of \( 1/\sqrt{E(\text{GeV})} \) at two different vertical tilt angles 0° and 2.5°.

4 - (a) The calorimeter response uniformity is shown at 8 GeV. A horizontal scanning was done through four adjacent modules. At the axis origin a small disuniformity (7%) is visible between two modules which are 'mechanically' separated. No similar effect is seen between modules only 'optically' separated.
(b) Same data are rebinned in 0.24 mm intervals in order to show the periodicity of the single fibre position in horizontal coordinate (four fibres per module).

5 - (a) Comparison between reconstructed \( \langle x \rangle \) and actual x horizontal coordinate at 8 GeV. x is measured with the beam wire chambers. \( \langle x \rangle \) is determined as the 'centre of gravity' of the energy deposited in the various calorimeter modules. The scanning was done through four adjacent modules.
(b) Comparison between reconstructed \( \langle x \rangle_c \) and actual x horizontal coordinate at 8 GeV. \( \langle x \rangle_c \) is determined by the algorithm described in Sect.3b. The waving behaviour shown in (a) is now corrected to a nearly straight one.

6 - (a) Further comparison between reconstructed \( \langle x \rangle \) and actual x horizontal coordinate at 8 GeV. The x-interval corresponds to four modules, i.e. to 32 mm total path.
(b) Further comparison between reconstructed \( \langle x \rangle_c \) and actual x horizontal coordinate at 8 GeV.

7 - (a) Events impact point distribution at 8 GeV as a function of \( \langle x \rangle - x \). By fitting a gaussian function one finds \( \sigma_x = 1.12 \) mm. This result is obtained by a simple 'centre of gravity' algorithm (see Figs. 5a and 6a).
(b) Events impact point distribution at 8 GeV as a function of \( \langle x \rangle_c - x \). By fitting a gaussian function \( \sigma_x = 1.07 \) mm is obtained by a more sophisticated algorithm (see Sect.3b and Figs. 5b and 6b).

8 - Impact point resolution of the electron shower \( \sigma_x \) as a function of the electron energy. Experimental points are obtained analysing the data with the algorithm described in Sect.3b both for small and large modules, i.e. for a module horizontal size of 8 mm (crosses) and 24 mm (squares) respectively. A contribution to the energy-independent term of the order of 0.1 mm is compatible with the beam chambers resolution. Notice that the vertical tilt angle is 2.5°.

9 - Distribution of single 8 GeV electron events (left histogram) and of two 4 GeV electrons events (right histogram) versus the ratio \( R \) defined in Sect.3c. Each 'two electron event' is obtained summing up the energy deposited by two events. Here the distance between the two electrons is 10 mm.
10 - Fraction \( F \) of two shower events which is correctly recognized versus the horizontal separation between the two shower axes. The energy of the single shower is 8 GeV and the energy of each of the two showers is 4 GeV. The module horizontal size is 8 mm in Fig.(a), and 24 mm in Fig.(b). The three set of data in each Figure refer to different fractional losses of single shower events: 2\%, 5\% and 10\% (from right to left respectively).
Fig. 1
Fig. 3

+ TILT=2.5° $\sigma(E)/E=16.0%/\sqrt{E}+1.6$

× TILT=0° $\sigma(E)/E=18.9%/\sqrt{E}+2.0$
Fig. 5
$E_e = 8$ GeV

Fig. 6
$E_\text{e} = 8 \text{ GeV}$

$\sigma = 1.12 \text{ mm}$

$\langle X \rangle - X (\text{mm})$

$\sigma = 1.07 \text{ mm}$

$\langle X \rangle_{\text{CORR}} - X (\text{mm})$

Fig. 7
\[ \sigma_x = 2.7 / \sqrt{E(\text{GeV})} + 0.6 \text{ mm (LARGE MOD.)} \]
\[ \sigma_x = 2.8 / \sqrt{E(\text{GeV})} + 0.07 \text{ mm (SMALL MOD.)} \]

(vertical tilt angle = 2.5°)

Fig. 8
Fig. 9
Fig.10