RD1 - SCINTILLATING FIBRE CALORIMETRY

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Invited Talk presented at the
Third International Conference on Calorimetry in High Energy Physics
Corpus Christi, TX - 29 Sept. - 2 Oct. 1993
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1. Introduction

Pioneering work on electromagnetic scintillating fibre (SciFi) calorimetry started in the early 80's as soon as fibres with adequate optical properties became available. Following a deeper understanding of the compensation mechanism in hadron calorimetry, an extensive program of R&D on compensating fibre calorimetry was proposed in 1987 by P. Jenni, P. Sonderegger and R. Wigmans in the framework of the LAA Project at CERN. This project, known as SpaCal, carried out an exhaustive investigation of the properties and performances of Pb-SciFi prototypes in a non-projective geometry. In 1990 the RD1 Collaboration launched a program of a global and realistic approach to fibre calorimetry for LHC addressing the following items: projectivity, longitudinal segmentation, light detection, calibration, radiation hardness.

Four different prototypes were built and tested during the last two years by the RD1 Collaboration.

We describe in section 2 the construction and performance of a fully projective calorimeter built out of monolithic modules. We discuss in section 3 the optimisation of fibre calorimetry for LHC detectors. Experimental results from two high-resolution electromagnetic prototypes and preliminary results on a coarse resolution hadron calorimeter are reviewed in section 4, 5 and 6 respectively. The concept and performance of a new kind of light detector are then reported in section 7.

2. The projective EM-Hadronic prototype

2.1 The detector

The first goal of RD1 has been to test the feasibility of fully integrated Pb-SciFi calorimetry with a projective geometry. We built a modular fibre calorimeter made of 19 fully projective towers. The modules had the shape of one quadrant of a pyramid trunk with a front face of about 4 x 4 cm², a back face of about 10 x 10 cm² and a depth of 200 cm (Fig. 1). Each module contains 2346 fibres with a diameter of 1 mm. The fibres are embedded in a lead matrix in a hexagonal pattern. The fibre spacing is 2.22 mm (centre to centre), which gives a lead to fibre volume ratio of about 4:1 to make the calorimeter quasi compensating.

All fibres run parallel to one another in the direction of the incoming particles. Therefore, some of them run all the way from the front face to the back, whereas the
fibres in the sloping part of the module become increasingly shorter as they approach the outer edge. These fibres start at progressively increasing distances from the front face of the module, with a pitch of about 7 cm (Fig. 2). We took advantage of this feature to obtain some kind of "longitudinal" segmentation in the read-out. All fibres running up to the front face of the calorimeter and the first two rows of shorter fibres were bunched together and named "electromagnetic section". The remaining fibres starting at 20 cm from the front face and beyond, were also bunched together and named "hadronic section". The e.m. section of each module contains 399 fibres, the hadronic section 1947.

The lead structure of the modules was constructed by assembling extruded grooved lead plates with half holes on each side. A 5 mm thick tin layer was deposited electrolytically on each side of the plates. Next the plates were stacked in parallelepipedal blocks with a cross section of about 10 x 14 cm^2 and brazed together by heating the stack.
for 12-14 hours at 245°C. The resulting blocks were then machined in such a way that two modules with the desired geometry were obtained from each block.

2.2 Experimental results

One of the major concerns about the performance of the detector was the uniformity of response at the boundary regions between adjacent modules. Since the fibres in the sloping parts of the modules were cut perpendicularly to their axis to preserve the reflected light component, there is a local deficiency of plastic in these boundary regions, which translates into a smaller sampling fraction and hence a smaller response, compared to the central regions of the towers (see Fig. 3).

Fig. 3 A detail of the sloping edge of a module

This effect was investigated using 80 GeV electrons. Fig. 4 shows a horizontal scan of the detector surface made with electrons. The response of the detector drops by ~10% at the boundaries between adjacent modules.

Fig. 4 Average calorimeter response for 80 GeV electrons as a function of the impact point

The energy resolution of the prototype was studied with electrons and pions from 10 to 150 GeV hitting the centre of the detector. The particles hit the calorimeter with an angle of 3° with respect to the fibre direction to avoid channelling effects.
Fig. 5 The energy resolution for electrons as a function of energy. The lines are the results of best fits to the experimental data.

The measured energy resolution (Fig. 5) for electrons is:

\[
\frac{\sigma}{E} = \frac{(12.74 \pm 0.46)\%}{\sqrt{E\text{(GeV)}}} + (1.94 \pm 0.02)\% 
\] (1)

\[
\frac{\sigma}{E} = \frac{(17.49 \pm 0.03)\%}{\sqrt{E\text{(GeV)}}} \otimes (2.70 \pm 0.01)\% 
\] (2)

The result of the fit is slightly worse (for the constant term) than the one published by the SpaCal Collaboration\(^9\), because of the non-uniformity effects described above.

The energy resolution and lateral shower containment were studied with 20, 40, 80 and 150 GeV pions entering the calorimeter in its central region at an angle of 3\(^\circ\) with respect to the fibre axis. The e/\(\pi\) signal ratios, corrected for the signal nonuniformities discussed above, were compared to the e/\(\pi\) signal ratios determined for a much larger detector with the same composition\(^9\), in order to estimate the average fraction of the lateral energy leakage (\(f_{\text{leak}}\)). It turns out that the prototype contains 70-75% of the hadronic shower, depending on the energy. Because of the larger \(\pi^0\) content, high energy showers are better contained than low-energy ones.
The results of the measurements are well described by

$$\frac{\sigma}{E} = \frac{49.6\%}{\sqrt{E(\text{GeV})}} + 6.5\%$$  \hspace{1cm} (3)

The energy resolution is clearly affected by the incomplete shower containment. These effects were studied by the SpaCal Collaboration\textsuperscript{11} and parametrized as follows:

$$\frac{\sigma}{E} = \sqrt{\left(\frac{c_1}{\sqrt{E}}\right)^2 + \left(\frac{\text{leak}}{\sqrt{E}}\right)^2 + c_2}$$  \hspace{1cm} (4)

After determining the leakage fraction $\text{leak}$, we find that our data are best described by an expression of this type when $c_1 = 35.3\%$ and $c_2 = 1.8\%$. These values are in good agreement with the ones published in ref. 9.

A more detailed description of the performance of this detector can be found in ref. 14.

3. Optimisation for LHC Physics

The energy resolution for electrons of a 1 mm fibre compensating calorimeter has been measured\textsuperscript{9} to be 12.9%/√E + 1.2% for electromagnetic showers and 30.6%/√E + 1.0% for pions. These resolutions are not well matched to LHC/SSC experiments; in particular a scaling term ≤ 10% and a constant term ≤ 1% is required for the search of $H \rightarrow \gamma\gamma$; due to pile up effects no physics measurement would benefit from an hadronic resolution better than 50%/√E+2%. A correct solution is then a segmented calorimeter with a better resolution e.m. compartment and a coarser hadronic section.

The energy resolution of a sampling calorimeter is essentially determined by two factors: the fraction and the frequency of sampling. The sampling fraction of a compensating Pb scintillating fibre device is very small; an increase of the sampling fraction would enhance the performance. However a large increase of this fraction has several disadvantages, namely departure from compensation and a less compact detector. Another way to improve the performance is to increase the sampling frequency using thinner fibres while keeping constant the Pb to scintillator ratio. This solution allows for a compensating device at the cost of a more complex construction.

The RD1 Collaboration has tested both options building two prototypes, one with 1 mm fibres and a Pb/fibre volume ratio of 1.8/1 and one with 500 μm fibres.

4. 500 μm fibre prototype

4.1 Construction

The detector was assembled using lead sheets (1. x 80. x 300. mm$^2$) in which U-shaped grooves were machined. The plates were stacked together to form a structure with a front face of 80x80 mm$^2$ and a depth of 300 mm, corresponding to 41 X$_0$. The structure is held
mechanically, no glue or solder is applied. The detector contains in total 5472 fibres and the volume ratio of lead to plastic is approximately 4:1. All the fibres run parallel to one another in the direction of the incoming particles.

The calorimeter is subdivided in four square towers with a surface of 40 x 40 mm² each. This is achieved by grouping the fibres sticking out at the rear end of the detector. The fibres were bunched together into hexagonal bundles, machined and diamond cut, and coupled through light guides to photomultipliers.

4.2 Experimental results

The energy resolution for electrons was studied using particles of 10, 20, 40, 80 and 150 GeV entering the calorimeter at an angle of 2° respect to the fibre direction. The results are plotted in Fig. 6 as a function of energy. The resolution can be parametrized as:

\[
\frac{\sigma}{E} = \frac{(9.2 \pm 0.3)\%}{\sqrt{E\text{(GeV)}}} + (0.63 \pm 0.05)\%
\]

\[
\frac{\sigma}{E} = \frac{(10.9 \pm 0.2)\%}{\sqrt{E\text{(GeV)}}} \oplus (1.11 \pm 0.05)\%
\]

The linear fit (χ² = 2.6/df) gives a somewhat better description of the data than the quadratic one (χ² = 3.2/df) as observed before⁹.

![Energy Resolution Plot](image)

**Fig. 6** The energy resolution for electrons as a function of the square-root of the energy. The lines are the results of fits to the experimental data.
Simple models predict the scaling term varying as the ratio of the square-roots of the fibre's diameter and the constant term as the inverse square-root of the number of fibres involved in the shower development\textsuperscript{15}.

When we compare these results with the ones obtained by the SpaCal Collaboration\textsuperscript{9} for a similar detector with 1 mm thick fibres and the same sampling fraction, it turns out that the scaling term of our detector has improved by a factor approximately $\sqrt{2}$ and the constant term by about a factor 2.

A more detailed description of the performance of this detector can be found in ref. 16.

5. High sampling fraction projective prototype

5.1 Construction

The prototype consists of six mechanically independent modules as shown in Fig. 7. The projectivity of the detector is concentrated in the two central modules. The non-projective modules have a cross section of 80 x 80 mm\textsuperscript{2}, the projective ones a front face of 40 x 80 mm\textsuperscript{2} and a back face of 80 x 80 mm\textsuperscript{2}, the depth is of 300 mm corresponding to 30 $X_0$. Each module is made stacking fifty 1.5 mm thick lead plates extruded with U shaped grooves 1.1 mm deep with a pitch of 1.6 mm. The grooves are arranged in a square geometry. This corresponds to a Pb/fibre volume ratio of 1.8/1. A 50 $\mu$m layer of low melting point alloy (Wood alloy: 48% Bi, 20% In, 20% Pb, 12% Sb, 58$^\circ$ C melting point) was deposited on each plate, the module was then filled with a set of fibres to prevent the alloy from entering the grooves, and the stack brazed at 70$^\circ$C for approximately two hours. The fibres were then extracted to be used for the next module and replaced by new ones. On the ground of MonteCarlo simulations, to avoid the non uniformity problems at the boundary of projective modules, these were stacked using lead plates of diminishing length to create the "staircase" geometry shown in Fig. 8. The fibres of each module are grouped in four independent bundles, each bundle is connected through a light guide to a photomultiplier.

Fig. 7 Schematic view of the calorimeter
5.2 Experimental results

The calorimeter has been exposed to electron beams of energies ranging from 5 to 150 GeV.

A fine horizontal scan has been performed in the vicinity of the "staircase" to check the uniformity of response. The results are shown in Fig. 9. The origin of the coordinates corresponds to the boundary between the modules. The signal non-uniformity is well below 2% demonstrating that this geometry fixes the boundary problem.
The energy resolution of the prototype has been measured with electrons entering the centre of the detector with an angle of 4° in the horizontal plane and 6° in the vertical plane. We have performed both a linear and a quadratic fit to the data points, the results are shown in Fig. 10.

\[
\frac{\sigma}{E} = \frac{(8.30 \pm 0.08)\%}{\sqrt{E} \text{(GeV)}} + 0.57\% \tag{7}
\]

\[
\frac{\sigma}{E} = \frac{(9.63 \pm 0.35)\%}{\sqrt{E}} \oplus 1.01\% \tag{8}
\]

Fig. 10 The energy resolution for electrons as a function of energy. The dashed and dotted lines are the results of a linear and a quadratic fit respectively.

6. Coarse hadronic prototype

6.1 Design and construction

A possible choice to design a moderate resolution hadronic calorimeter that maintains the nice property of compensation (i.e. a Pb/fibre volume ratio of ≈ 4/1), is to act on the sampling frequency, increasing the fibre diameter. This clearly means a much
easier construction, but doesn't pay in terms of cost, because fibre price goes essentially by volume. The alternative solution of reducing the sampling fraction would, at first sight, imply a departure from compensation. However, the compensation condition requires simply a ratio of $= 4/1$ between lead and a hydrogen-rich material. It is then possible to use scintillating fibres inserted in plastic tubes keeping the correct plastic to lead volume ratio. RD1 has chosen 1 mm fibres in a 3 mm plastic tube; this allows a substantial saving in cost thanks to the reduction of a factor 9 of both fibre volume and photodetector surface, at the price, however, of a loss of the same factor in light yield.

We built a prototype consisting of nine semiprojective towers with a front face of 102 x 102 mm$^2$, a back face of 102 x 174 mm$^2$ and a depth of 1700 mm (see Fig. 11), corresponding to 8.1 nuclear interaction length. We built each module stacking 29 extruded lead profiles 6 mm thick, having U shaped grooves of 3 mm to house the plastic tubes with a pitch of 6 mm (see Fig. 12). This structure corresponds to a Pb/plastic volume ratio of approximately 4:1. The plastic tubes were then inserted into the grooves. The lead profiles were glued together using a special double sided tape especially suited for lead. To get more mechanical strength, each module was placed in a 2 mm thick steel jacket. The fibres were then inserted and coupled to a photomultiplier by a light guide.

![Fig. 11 Front face of a tower as seen by a particle entering the detector.](image1)

![Fig. 12 Detail of the extruded lead profile with the plastic tube and the fibre](image2)
6.2 Experimental results.

The calorimeter has been exposed to pion beams and, for calibration purposes, to electron beams. Electron data have been analysed in view of determining the energy resolution to cross-check MonteCarlo simulations made using the GEANT 3.15 package. A linear fit to the data yields:

\[
\frac{\sigma}{E} = \frac{(33.1 \pm 1.5)\%}{\sqrt{E(\text{GeV})}} + (3.3 \pm 0.2)\% \tag{9}
\]

The MonteCarlo prediction is:

\[
\frac{\sigma}{E} = \frac{(34.3 \pm 2.4)\%}{\sqrt{E(\text{GeV})}} + (3.0 \pm 0.4)\% \tag{10}
\]

This device was clearly not devised for electron detection. Electrons are anyway a very fine probe of the structure of the calorimeter. The nice agreement between data and simulation is then a good proof of the accuracy of the simulations.

A horizontal scan with pions (Fig. 13) has furthermore demonstrated that the "staircase" geometry guarantees a sufficient degree of uniformity in the transition region between towers.

![Graph](image)

Fig. 13 Results of a pion horizontal scan in the boundary region.
The energy resolution for pions has been measured with pion beams of energies ranging from 10 to 150 GeV. The results are plotted in Fig. 14. A best fit to the experimental points gives:

$$\frac{\sigma}{E} = (77.3 \pm 2.6)\% \sqrt{E(\text{GeV})} + (3.5 \pm 0.4)\%$$  \hspace{1cm} (11)$$

![Resolution for pions / hadronic prototype 92](image)

Fig. 14 Energy resolution for pions. The results of GEANT 3.15 simulations are also shown.

The GEANT simulation gives a prediction of:

$$\frac{\sigma}{E} = \frac{77.3}{\sqrt{E}} + 3.54\%$$  \hspace{1cm} (12)$$

The MonteCarlo reproduces also well other details of the detector such as the energy sharing between the single towers. This make us confident to use it to predict the performance of an almost full containing device (5 x 5 towers):

$$\frac{\sigma}{E} = \frac{(69.6 \pm 5.0)\%}{\sqrt{E(\text{GeV})}} + (2.7 \pm 0.4)\%$$  \hspace{1cm} (13)$$
7. Proximity Focused Hybrid Photodiode Detector (PFHPD)

Limited dynamic range, stability, sensitivity to magnetic fields and large power consumption are properties of photomultipliers that make them not very well suited for use as light detectors for calorimetry at Supercolliders. In recent years an old idea of the 60's 17-19 has been revived20 to overcome these problems: replace the dynode chain by a silicon detector working in electron bombardment mode. The detector is composed of a photocathode deposited just as in a conventional PMT on a glass or fibre-optics input window and of an output surface equipped with a reverse biased silicon detector (anode) placed in close proximity (~ 1.5 mm) to the photocathode, which acts as an electron detector. Those components are vacuum sealed to both ends of a ceramic cylinder. A large electric field of about 10 KV, is applied between the two electrodes (see Fig. 15). The photoelectrons produced in the photocathode are accelerated by the electric field before entering the silicon detector. There is a thin passivation layer on the silicon which corresponds to a mean energy loss HF without pair creation. The electron gain is therefore (HV - HF ) / 3.62 and can reach a few thousands.

![Diagram of the Proximity Focused Hybrid Photodiode Detector](image)

Fig. 15 Principle of the Proximity Focused Hybrid Photodiode Detector

Two prototypes have been built for RD1 by the DEP company. They differ only by the sizes of the silicon detectors with diameters of 6 mm and 8 mm respectively, the choice being dictated only by commercial availability. The photocathode diameter is 18 mm. The detectors were tested using a 10 mW GaAs laser delivering up to $10^8$ photons per nanosecond over a spot of 4 mm diameter. The gain has been measured to be linear at the level of 0.5% between 6 and 10 KV. Electron straggling in the Si passivated layer causes non linearity effects at lower voltages. The values of HF measured from the data are 3650 V and 3330 V for the two prototypes.

The dynamic range was measured at 10 KV with the bias set at 130 V on the silicon. The laser beam with a fixed intensity and a set of calibrated filters were used to cover the measures output charge range from 66 fC to 560 pC. Fig 16a is a plot of the measured versus the expected output charge.

The linearity is excellent. The ratio (measured-expected)/expected shown in Fig. 16b is consistent with zero at the 2% measurement accuracy level. To scale such a plot with the incident energy for calorimetric applications, an equivalence 1 GeV = 500 photoelectrons was used.
The ageing behaviour was measured under illumination by a yellow LED continuous light source. The high voltage was set at 8 kV for an initial gain of about 1200. The integrated output charge was 600 mC, the gain loss is linear with the integrated charge at a rate of 4% per 100 mC. These correspond to a 1.2% gain loss per year for a 1" Si detector on a calorimeter cell $\Delta\eta \times \Delta\phi = 0.02 \times 0.02$ at $\eta = 2$ for an integrated luminosity of $10^5$ pb$^{-1}$.

A set of measurements was made with an axial magnetic field, parallel to the direction of the 10 kV electric field, up to 0.7 Tesla. The laser light pulses were fed to the input window via an optical fibre and a diffusing disk whose diameter was the same as that of the Si detector. The results are shown in Fig. 17a. As expected, the output charge remains constant within the 2% measurement accuracy, a confirmation of the insensitivity of such a device to axial fields. The measurements have now been extended to 2 Tesla with the same result.
For the transverse field orientation, measurements were made up to 0.2 Tesla. Results are shown in Fig. 17b. This is somewhat better than the results of a simulation that predicts a continuous slow decrease of the signal with the strength of the magnetic field as shown in Fig. 17c. Such a difference is likely due to a light spot diameter slightly larger or smaller than the size of the Si detector, which would postpone the decrease of the signal due to the curvature of the electron trajectories.

A more detailed description of the performance of this detector can be found in ref. 21.

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**Fig. 17 Tests in magnetic field.**

- **a)** Output charge in axial field.
- **b)** Measured signal in transverse field for different voltages.
- **c)** Expected effects in transverse field.
References

16. J. Badier et al. 'Test Results of an Electromagnetic Calorimeter with 0.5 mm Scintillating Fibers Readout' submitted to Nucl.Instr.Methods.