EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/DRDC/92-19
DRDC/P32 Add.1
10 March 1992

Addendum to the:

Proposal for continuing studies on Lead/Scintillating Fibres Calorimetry (LFC)

G. Anzivino[8], F. Arzarello[1], J. Bai[5,13], G. Bari[1], M. Basile[1,2], L. Bellagamba[1], C. Bencheikh[4], D. Boscherini[1], G. Bruni[1], P. Bruni[1], V. Buzuloiu[7,13], G. Cara Romeo[1], M. Chiarini[1], L. Cifarelli[1,9], F. Cindolo[1], F. Ciralli[1], A. Contin[1,2,3]†, M. Dardo[10], S. DePasquale[1], R. De Salvo[3]‡, F. Frasconi[1], A. Gheorge[7], P. Giusti[1], W. Hao[5,*], H. He[5,13], G. Iacobucci[1], G. Laurenti[1,3], P. Liparulo[11], L. Liu[5,13], M. Lundin[12,3], G. Maccarrone[1], A. Margotti[1], T. Massam[1], M.R. Mondardini[12], R. Nania[1], V. Peskov[6,13], G. Sartorelli[1,2], R. Timellini[1], K. Wang[5,13], Y. Wang[5], X. Xia[5,13], C. Xu[5], C. Yang[5,13], M. Zhao[5,13] and A. Zichichi[1,2,3]

1) INFN, Sezione di Bologna, Italy.
2) Università di Bologna, Italy.
3) CERN/LAA, Geneva, Switzerland.
4) Haute Commisariat à la Recherche, Ain-Oussura, Algeria.
5) IHEP, Beijing, People's Republic of China.
6) Institute for Physical Problems, Moscow, Russia.
7) Institute of Atomic Physics, Bucarest, Romania.
8) INFN, Laboratori Nazionali di Frascati, Italy.
9) Università di Napoli, Italy.
10) Università di Torino and INFN, Sezione di Torino, Italy.
11) Politecnico di Torino and INFN, Sezione di Torino, Italy.
12) Cornell University, Ithaca, NY, USA.
13) World Lab Fellowships, Lausanne, Switzerland.
*) Now at NIKHEF, The Netherlands.

† spokesman
‡ contactman

1. Introduction.

Purpose of this Addendum to Proposal DRDC/P32 is to answer some questions brought up by the DRDC in its meeting of 30-31 January 1992, concerning the construction of new lead/scintillating fibre prototypes, to be tested during 1992 in a SPS e/π beam.

The points to be clarified are the following:

1. Physics applications for the proposed design and performance.
2. Design and geometry.
3. Cost.
4. Why a new prototype is required.

In the following sections, all these points will be discussed in detail.

2. Physics applications for the proposed design and performance.

The main goal of the R&D on lead/scintillating fibre ("spaghetti") calorimetry, set at the beginning of the LAA project, was to develop an integrated electromagnetic and hadronic compensating calorimeter. This calorimeter is intended to precisely measure and localize the energy flow of the events, to identify particles (electrons, γ's, hadrons, μ's, weak interacting neutrals), and to trigger on interesting events, in a multi-TeV hadron collider experiment.

These physics requirements translate into the following requirements for the calorimeter:

a) Good overall resolution with a small constant term ($\leq 1\%$).
b) Linear response with a gaussian line-shape.
c) High granularity.
d) Fast and uniform response.
e) Low noise.
f) Hermeticity.
g) e/π discrimination signal easy to extract.
h) Radiation resistance.

Considerations on the cost of the calorimeter itself, and, more important, of the rear μ detector, indicate a further requirement:

i) Compactness.

This last requirement also reduce the shower dimensions, thus minimizing pile-up noise.

A progression of calorimeter prototypes have been built and tested during the last four years in the framework of the LAA Project [1-12], proving that the spaghetti calorimeter can satisfy many, if not all, of the supercollider calorimeter requirements.

In particular, the following results have been obtained.

2.1. Energy resolution.

The energy resolution of the spaghetti calorimeter was measured to be:

$$\frac{\sigma}{E} = \frac{13 \div 15\%}{\sqrt{E[\mathrm{GeV}]}} + 0.5\% \text{ for electrons,}$$

and

$$\frac{\sigma}{E} = \frac{28\%}{\sqrt{E[\mathrm{GeV}]}} + 2.5\% \text{ for single hadrons.}$$

The constant term for single hadrons reduces to 1% after some corrections for attenuation length of the fibres are applied. Thanks to the near compensation ($e/h \sim 1.15$) achieved in the spaghetti calorimeter prototype, the energy resolution for jets is better than for single hadrons.

Some methods have also been identified which will allow to control the calibration constants of the different detector modules during the experiment to within 1%. Further studies are in progress.

2.2. Linearity and response line-shape.

The response of the spaghetti calorimeter over the tested range ($3 \div 150$ GeV) was measured to be linear within 0.5% for electrons, and within 3% for pions after corrections for attenuation length effects. Correspondingly, the response, as expected for a (nearly) compensating calorimeter, is (nearly) gaussian. Further improvements of the on-line hadron line-shape and resolution can be achieved by using fibres with longer attenuation length and improving the compensation (see section 5).

2.3. Granularity.

Prototypes with different granularity have been built. The precision in determining the position of the incident particles was measured to be:

$$\sigma = \frac{17.1\,\mathrm{mm}}{\sqrt{E[\mathrm{GeV}]}} \text{ for electrons (granularity} = 50\,\mathrm{cm}^2\text{),}$$

$$\sigma = \frac{4.0\,\mathrm{mm}}{\sqrt{E[\mathrm{GeV}]}} \text{ for electrons (granularity} = 10\,\mathrm{cm}^2\text{),}$$

$$\sigma = \frac{31.4\,\mathrm{mm}}{\sqrt{E[\mathrm{GeV}]}} \text{ for single hadrons (granularity} = 50\,\mathrm{cm}^2\text{).}$$

Given the small Moliere radius of the spaghetti calorimeter, an electron/electron (or γ/γ) separation below 1 cm can be achieved [13]. Further tests are needed on this subject (see section 5).

2.4. Response time and uniformity.

The response of the scintillating fibres to charged particles is intrinsecally very fast (few ns). This reflects in very short collecting times for showering particles. In particular, 75% of the electron signal and 67% of the hadron signal is collected within 15 ns without any signal shaping and with 90 m cables, and both electron and hadron showers are fully mesured after 100 ns. Signal shaping and local read-out can reduce this value by a large factor.

The non-projective calorimeter response was also measured to be uniform across the modules, and across module boundaries. A small non-uniformity for electromagnetic showers exists across module boundaries in the projective prototype. This is due to a local undersampling of the shower which can be corrected (see section 5).

2.5. Low noise.

The signal from the scintillating fibres of the spaghetti calorimeter is large. At least 350 photoelectrons are delivered per GeV of deposited energy, while the noise is typically much below the single photoelectron level.

A high signal-to-noise ratio is essential to measure the energy lost by muons traversing the calorimeter (3÷4 GeV). At high (> 100 GeV) energy where bremmsstrahlung and e^+e^- pair production processes produce large fluctuations in the energy loss. These fluctuations are easily measured in the spaghetti calorimeter.

Infact, the r.m.s. width of the fractional energy loss is about constant at $\sim 5\%$ for energies above 50 GeV in a 10λ spaghetti calorimeter. This uncertainty, which adds to the resolution of the muon detector, may prove unacceptable for experiments which aim at an excellent muon measurement.

The spaghetti calorimeter, thanks to the very high signal-to-noise ratio, can measure the energy lost by muons with a 14% precision for energies above 50 GeV, thus reducing the uncertainty on the total muon energy to below 1%.

2.6. Hermeticity.

A full hermeticity is achieved in the spaghetti calorimeter because all the read-out is located at the rear detector end.

2.7. e/π discrimination.

Several methods to discriminate between electrons and pions have been explored with the different prototypes. Two of them are particularly promising: the longitudinal sampling in the projective calorimeter that proved to be equivalent to an effective longitudinal segmentation and the signal width (at 20% of the peak). In combination, they give a 10^{-3} rejection against π in about 100 ns. Further rejection factors can be achieved with more sophisticated on-line and off-line analysis.

2.8. Radiation resistance.

The radiation resistance of scintillating fibres have been measured using short samples. The results show that the calorimeter can withstand 4 years at LHC at a pseudorapidit of 2.5 with only a small degradation in the performances.

A complete radiation hardness test programme is ongoing using the LIL and PS beams at CERN. Results on several fibre types should be available by the end of the year.

Note, in addition, that the spaghetti calorimeter is self-moderating in that it contains 20% of plastics. Therefore, the albedo neutron flux is naturally reduced.

2.9. Compactness.

The effective radiation length of the spaghetti calorimeter is 7.2 mm, the effective Moliere radius 20 mm, the effective nuclear interaction length 21 cm, and the average density 9.0 g/cm^3. These characteristics makes the spaghetti calorimeter extremely compact.

2.10. Conclusions.

The performances mentioned above allow the investigation of nearly all the physics of LHC/SSC. In particular, the energy resolution will be adequate to measure jet, single electron, single γ, W, Z cross-sections, and to search for top quark, high-mass ($m_H > 2m_W$) Higgs, or new IVBs. Coupled to the excellent hermeticity, the spaghetti calorimeter is also adequate to look for the production of new weakly interacting particles.

Due to its rather coarse electromagnetic resolution, the search for low-mass ($m_W < m_H < 2m_W$) Higgs in the most promising channel $H^0 \rightarrow \gamma\gamma$ will be somewhat more difficult with a spaghetti calorimeter than with an homogenous electromagnetic calorimeter, *e.g.* LXe or crystals with resolution $\sigma/E \sim 2\%/\sqrt{E}$. However, the capability of the spaghetti calorimeter to distinguish very closeby γ's may turn out to be a decisive advantage if the backgound from jets is much higher than expected from present calculations. Moreover, the very small Moliere radius of the spaghetti calorimeter and its very fast signal reduce to a minimum the effects due to energy pile-up from different events and from different bunch crossings.

3. Design and geometry.

Several ideas were tried in order to build self-supporting projective spaghetti modules structures (see for example [1]) but none of the techniques initially used proved to be satisfactory and most of them were quickly rejected.

Back in 1989-90 we made the first tests with one of the most promising techniques, extruded lead profiles brazed together to form Swiss cheese rods. When testing this idea we realized that that technique was difficult, expensive, not easily scalable and not suitable for high quality calorimetry. While most of the other technical problems could probably be solved we could not find any reasonable technique to safely feed the thousands of 1 mm diameter fibers in the 2 m long, 1.1 mm diameter holes. From the very beginning the result was poor uniformity and many dead fibers.

While a limited effort (few modules) continued in that direction the technique was abandoned for mass construction and we decided to build all the major prototypes (2 tons and 13 tons) with the pileup technique, namely laying layers of fibers over loose lead profiles (see fig. 1). This technique proved to be easy, much cheaper and fast and produced high quality calorimeters with constant term as low as 0.5%. Up to 100 kg of calorimeter per hour could be piled by a skilled crew of four.

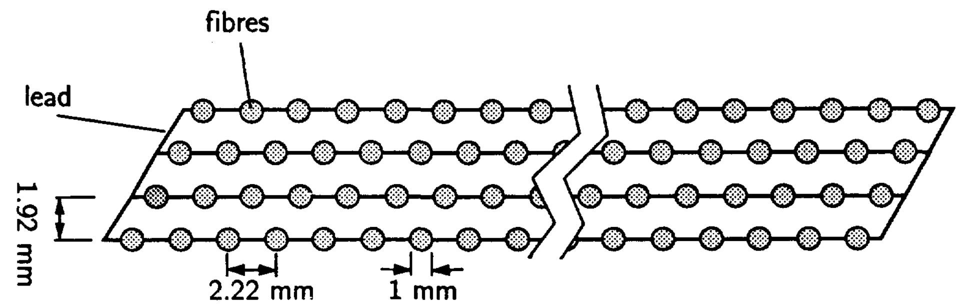

Fig. 1. Lead profile used to build the 2.5 and 15 tons prototypes.

Simple pile-up is however not suitable for the construction of self-supporting full projective modules[1]. The two main problems with piling up of loose profiles are that the profiles are aligned one to the other by the fibers themselves and that nothing keeps the profiles together after piling. A possible solution considered was to glue together fibers and lead; this technique was rejected due to cladding damage and different thermal expansion coefficients between fibers and lead.

A first step to come out of that impasse was to develop keying lead strips where the lateral alignment of the profiles is provided by special grooves and ridges in the profile itself (see fig. 2). We are also finalizing the development of machining techniques that will allow us to pre-cut the lead strips in a way that they can be piled up directly and quickly into projective modules.

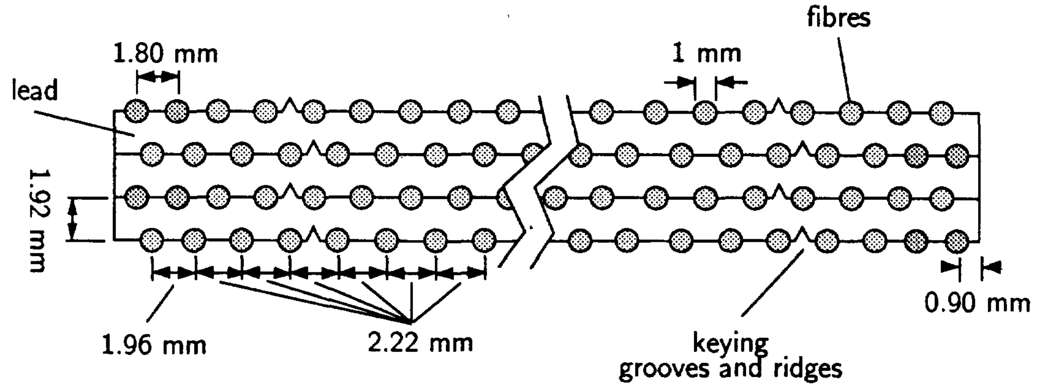

Fig. 2. Lead profile for the new projective prototype.

Once the projective module is piled up it will be slipped into a truncated pyramid shaped shell built out of 0.5 mm thick stainless steel sheet. This pyramidal sleeve would extend from 30 cm behind the module's front face to the photon detection region at the back covering only the hadronic part of the calorimeter.(see fig. 3).

Our programme is to build 2 m long pyramidal modules with a $30 \times 30\,\mathrm{mm}^2$ front face and a $75 \times 75\,\mathrm{mm}^2$ back face. The pyramid will be slanted in order to have two of its sides parallel to the fiber axis. In order to ease up the construction, minimize lead profile waste, and allow the use of different types of fibers in different volumes of the calorimeter we will pile up separately the $30 \times 30\,\mathrm{mm}^2$ cross section straight portion of the pyramidal module and the two side wedges completing it (see fig. 4).

A total of 36 modules will be built. The layout of the complete calorimeter is shown in fig. 5.

In the read-out, each module is subdivided into one straight section (electromagnetic and partly hadronic), and in one wedged section (only hadronic). The straight section of the four central modules will be further subdivided into 9 sections, giving a granularity of $1\,\mathrm{cm}^2$. The photomultipliers will be arranged at the rear end, as shown in fig. 6.

---

[1] Our previous prototype, built with this simple pile-up technique was projective in only one direction.

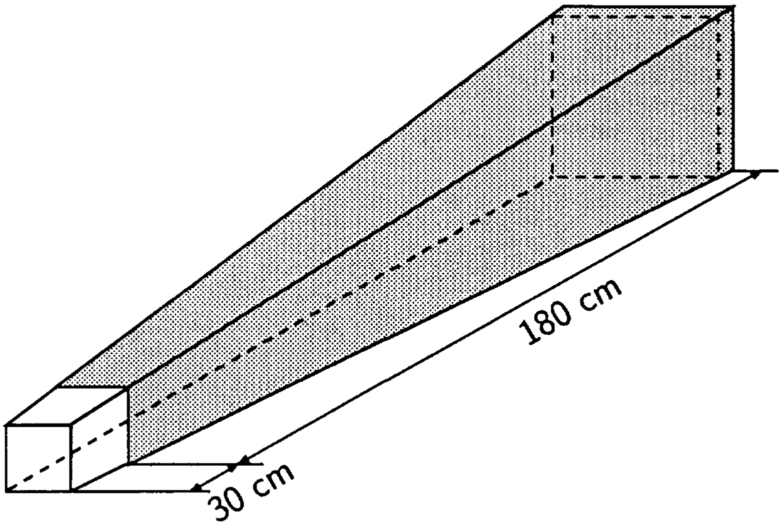

Fig. 3. Steel shell surrounding one projective module.

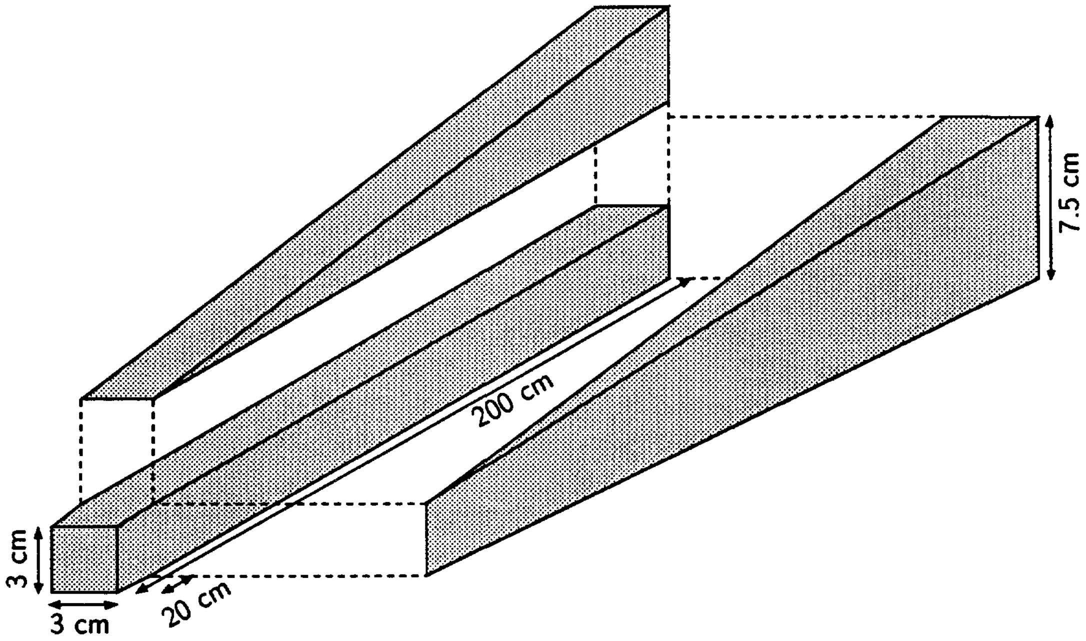

Fig. 4. Exploded view of one projective module.

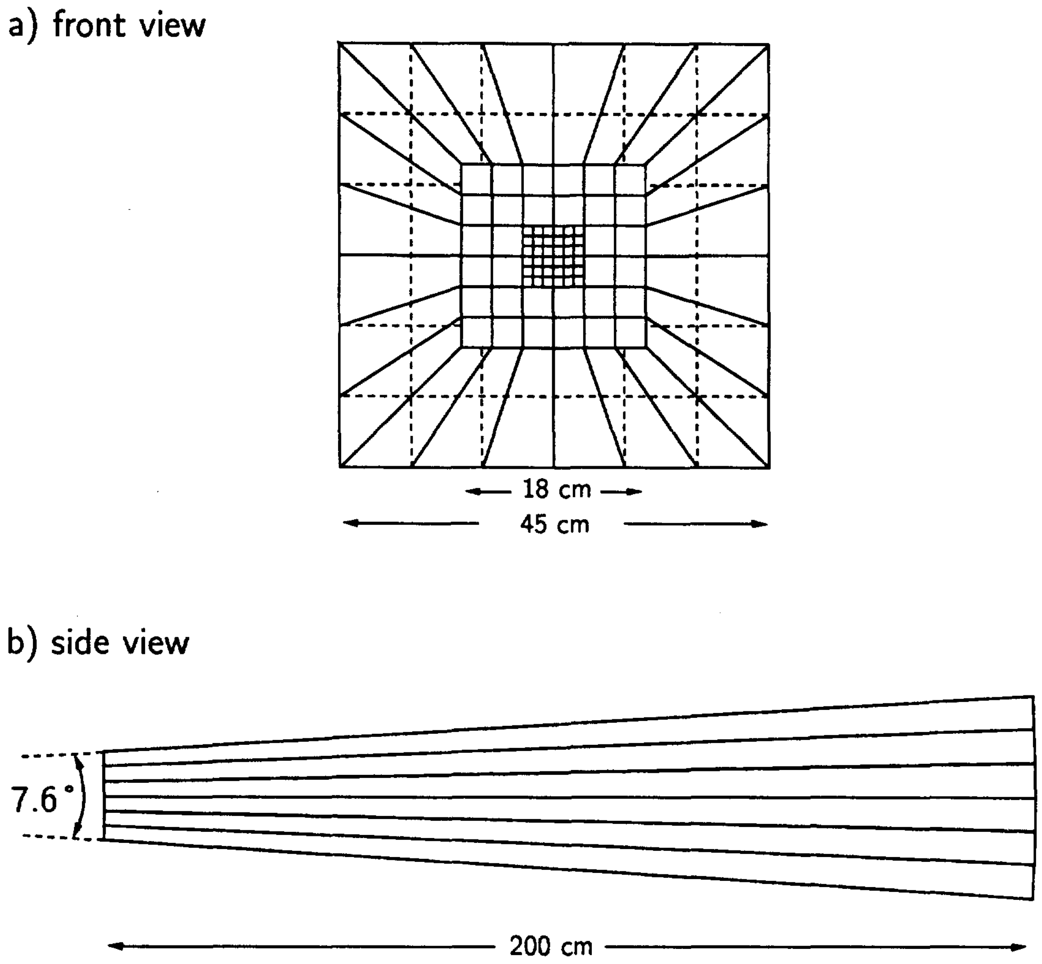

Fig. 5. Layout of the 36-modules calorimeter prototype.

Since the wedges are exposed only to hadronic showers they can be built cheaply, larger diameter fibers. The modular construction of each pyramid will allow the easy testing of different fiber choices in the electromagnetic sections (smaller fiber diameters or higher fiber to lead loading ratios can be fed in the straight part of the pyramid without changing the module's outer shape; if need be also the wedges load could be changed in order to compensate for changes in the straight part). It is true that with this design any choice of fiber for the electromagnetic section will have to be propagated also through part of the hadronic sector, but we estimate that the savings in the readout system and in support structure brought by this integrated electromagnetic and hadronic structure by far outweight the cost of using more expensive fibers in the hadronic volume.

The steel sleeve solution to hold together the modules is particularly attractive because with technologies borrowed from the automotive industry (steel sheet edge laser beam welds) the thin skin can be welded to thicker plates extending half meter out from the

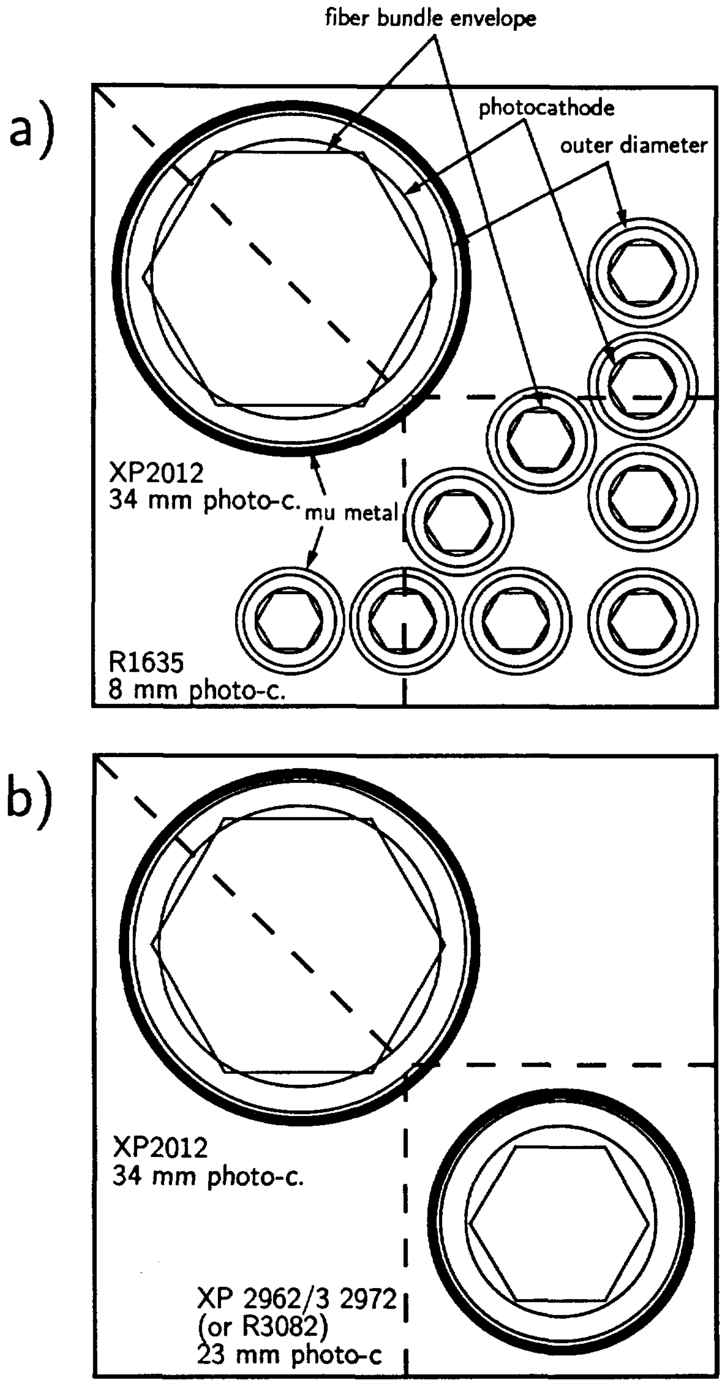

Fig. 6. Photomultiplier positions at the back of the modules: a) inner modules, b) outer modules.

back of the pyramidal module and in the light detector region. These plates, suitably shaped and riveted together in an eggcrate structure would constitute the support of a 4π calorimeter as the one described in ref [1].

4. Cost.

The total construction cost of the 36-modules (1.6 tons) prototype detector is about 35,000 SF (see Table I). Photomultipliers, high voltage system, and read-out electronics adds an extra 107,000 SF.

Table I. Construction cost of the prototype detector.

Item	Total cost
Fibres $\phi = 1.0\,\mathrm{mm}$ (600 m/module @ 0.5 SF/m)	10,800 SF
Fibres $\phi = 1.5\,\mathrm{mm}$(400 m/module @ 0.65 SF/m)	9,360 SF
Lead (45 kg/module @ 5 SF/kg)	8,172 SF
Light guides (15 SF/PM)	1,560 SF
Mechanics (110 SF/module + 10 SF/PM)	5,000 SF
TOTAL	34,892 SF

The construction cost is, therefore, about 1,000 SF/module, or 22 SF/kg. Note, however, that these are the present costs of the various items. Quotes for larger amounts are sensibly lower (for example, the CHORUS experiment will pay the 1 mm fibres only 0.3 SF/m), leading to prices below 15 SF/kg.

The construction of this prototype is part of the INFN CPF experiment, performed in collaboration with the LAA Project. Its cost will be completely covered either by INFN or (for a limited amount) by LAA.

5. Why a new prototype is required.

Several reasons justify the construction of a new projective prototype. Some are purely technical, others concerns the improvement of the performances of the calorimeter.

First of all, we want to test the new construction scheme that may prove to be very close to the final one and well adapted to a large scale production. Each module will also be self-supporting and cantileverable. Some technical details have to be tested, namely the reproducibility of the construction technique and the local changes in fibre density needed to correct the dip in response mentioned in section 2.4. A local oversampling at the edges of the lead profiles has been introduced (see fig. 2) to compensate for the dip in response observed in the previous projective prototype.

The improvements in the performances expected with the new prototype concern a better position resolution and a better electron/electron (or γ/γ) separation, thanks to the smaller dimensions of the electromagnetic modules (from $10\,\mathrm{cm}^2$ to $1\,\mathrm{cm}^2$), and a possibly better electromagnetic energy resolution due to a more careful choice of the fibres, which will be measured and selected automatically before use [14].

In addition, better studies on e/π rejection can be done, due to the larger size of the prototype. In fact, we expect to have a $90 \div 95\%$ containment of hadronic showers, compared to about 60% in the old projective prototype.

The better containment of hadronic showers allows also to study the degradation in the hadronic energy resolution expected using 1.5 mm fibres (instead of 1.0 mm) in the wedged sections, and the improvement of the on-line hadronic signal shape and linearity thanks to the use of shorter fibres in part of the hadronic sector.

Finally, the modular constrution of the prototype allows for easy modification of (some) modules, in order to test different types of fibres or structures with different sampling fractions.

We estimate that most of these results can not be derived from presently available data. Moreover, we think that the construction of this prototype is a decisive step towards the establishment of spaghetti calorimetry as a mature technique, immediately applicable to experiments in multi-TeV hadron colliders.

References.

[1] R. DeSalvo, "Dream on a Supercollider Spaghetti Calorimeter", Proceedings of the Workshop on Calorimetry at the Supercollider, March 13-17, 1989, Tuscaloosa, Alabama, World Scientific (ed. R. Donaldson, M.G.D. Gilchriese), page 383.

[2] R. DeSalvo et al., Nucl. Instr. and Meth., A279 (1989) 467.

[3] D. Acosta et al., Nucl. Instr. and Meth. A294 (1990) 193.

[4] D. Acosta et al., Nucl. Instr. and Meth. A302 (1991) 36.

[5] D. Acosta et al., Nucl. Instr. and Meth. A305 (1991) 55.

[6] D. Acosta et al., Nucl. Instr. and Meth. B62 (1991) 116.

[7] D. Acosta et al., Nucl. Instr. and Meth. A308 (1991) 481.

[8] D. Acosta et al., Nucl. Instr. and Meth. A309 (1991) 143.

[9] B. Bencheikh et al., "First results on the spaghetti calorimeter projective prototype", presented at the V Pisa Meeting on Advanced Detectors, 25-31 May 1991, to be published in Nucl. Instr. and Meth..

[10] A. Contin et al., "On the calibration of the electromagnetic component of a spaghetti calorimeter at a multi-TeV hadron collider", presented at the V Pisa Meeting on Advanced Detectors, 25-31 May 1991, to be published in Nucl. Instr. and Meth..

[11] D. Acosta et al., "The performances of a lead/scintillating fiber calorimeter at LHC/SSC compatible gate widths", preprint CERN-PPE/91-195.

[12] D. Acosta et al., "Detection of muons with a lead/scintillating fiber calorimeter", in preparation.

[13] G. De Zorzi, LEP5, private communication. The same group has measured a position resolution of $2.7\,\mathrm{mm}/\sqrt{E[\mathrm{GeV}]}$ with a granularity of $0.65\,\mathrm{cm}^2$.

[14] V. Buzuloiu et al., "Testing scintillating fibres for the spaghetti calorimeter: a feasibility study", LAA internal note, February 1991.