THE HIGH RESOLUTION SPAGHETTI HADRON CALORIMETER

Proposal

April 27, 1987

P. Jenni and P. Sonderegger
CERN, Geneva, Switzerland

H.P. Paar and R. Wigmans*
NIKHEF-H, Amsterdam, The Netherlands

ABSTRACT

We propose to build a prototype for a hadron calorimeter with scintillating plastic fibres as active material. The absorber material is lead. Provided that these components are used in the appropriate volume ratio, excellent performance may be expected, *e.g.* an energy resolution of $30\%/\sqrt{E}$ for jet detection. The proposed design offers additional advantages compared to the classical sandwich calorimeter structures in terms of granularity, hermiticity, uniformity, compactness, readout, radiation resistivity, stability and calibration.

⋆ contact person

1. INTRODUCTION

Large calorimeters play an increasingly important role in detectors for high-energy physics experiments. The reasons for this have been outlined many times in the literature[1]. Since calorimetry is based on statistical processes, the measurement accuracy increases with energy. For tracking detectors based on momentum analysis in a magnetic field, the opposite is true. Therefore, at increasing energies calorimetry can become a very powerful tool for accurately detecting interaction products. In addition, calorimeters offer unique possibilities to recognize rare events at the trigger level and to measure the characteristics of these selected events with high precision under severe background conditions, with a compact instrument. With increasing center-of-mass energies the demands on the calorimeter performance will increase as well[2]. The interesting events will be extremely rare, the precision required for some of the expected new physics asks for pushing to the ultimate limits, the interaction rates will become very high (SSC, LHC), and compactness becomes a key issue to keep the detector affordable. Experiments at new machines like Tevatron and HERA distinguish themselves by and were justified mainly on the basis of the (expected) calorimeter performance. For experiments at proposed machines like SSC, LHC and CLIC the best possible calorimetry is of absolutely crucial interest.

Calorimeters for the detection of electromagnetically interacting particles (e,γ) are well understood and can be reliably simulated in great detail by Monte-Carlo techniques (e.g. EGS4). This is by no means the case for hadron calorimeters. As a consequence, progress in that area of detector technology had to proceed on a trial-and-error basis for a long time. Many results obtained in this process were considered extremely confusing.

The crucial role of the so-called e/h signal ratio for the energy resolution was already recognized in the early days of hadron calorimetry[3]. The R807 group at CERN demonstrated that energy resolutions of $35\%/\sqrt{E}$ could be achieved for hadron detection with their uranium-scintillator sandwich calorimeter, which had an e/h ratio close to the desired value 1.0[4]. Measurements performed by HELIOS recently showed that the energy resolution of this detector scales with $1/\sqrt{E}$ up to the TeV regime, and that deviations from signal linearity are negligible over 3 orders of magnitude in energy[5] .

Measurements performed with non-compensating ($e/h \neq 1$) devices, however, showed considerable deviations from linearity, and energy resolutions σ/E that do not improve as $1/\sqrt{E}$ with increasing energy[6] . The constant term that has to be introduced in order to describe the energy resolution is typically 5% and, therefore, dominates the result at energies greater than 100 GeV, where the new physics has to be found.

However, the use of ^{238}U as absorber material is by no means a guarantee for superior performance. Prototype tests by SLD and D0, using liquid argon readout, gave disappointing results, to the extent that SLD even abandoned the idea of using uranium and switched to a lead absorber that gave results of similar quality. Also the combination uranium-scintillator turned out not to be magic: WA78 found over-compensation ($e/h \approx 0.8$) and rather poor energy resolutions[7] . On the other hand ZEUS, who basically copied the HELIOS design for their prototype studies, found equally good performance[8] .

Recently, understanding of hadron calorimetry has considerably improved. One of us has systematically investigated in great detail the response of a sampling calorimeter to the various components of a hadron shower[9] . It turned out that the calorimeter performance in terms of energy resolution and signal linearity is crucially determined by its response to the abundantly present soft neutrons in the shower. The presence of a considerable fraction of hydrogen atoms in the readout medium is essential for the best possible performance. Firstly, this allows one to tune e/h to the desired value (1.0) by choosing the appropriate sampling fraction. And secondly, efficient neutron detection via recoil protons in the readout medium itself reduces considerably the effect of fluctuations in binding energy losses at the nuclear level, which dominate the intrinsic energy resolution.

The apparently confusing experimental results mentioned before were reproduced rather accurately in this study. It was shown that the R807 Collaboration had chosen the optimal sampling fraction in their design. An important conclusion of the paper was that signal equalization, or compensation ($e/h = 1$) is not a unique property of ^{238}U, but can be achieved with other absorber materials as well. In particular, a compensating lead-scintillator calorimeter was predicted. This should have a somewhat unconventionally small sampling fraction, achieved by a thickness ratio of passive to active material of 4 to 1.

This prediction was recently experimentally confirmed by Kötz *et al.* from the ZEUS Collaboration[10] . They built a 10 mm lead, 2.5 mm polystyrene scintillator sandwich calorimeter and found that it had all the nice properties of a perfectly compensating device. The hadronic signal distribution was to a very good approximation gaussian (only true if $e/h = 1$), the hadronic signal was linear over the measured energy range (3 − 75 GeV) and the energy resolution σ/E was found to scale as $43\%/\sqrt{E}$ over the same range (predicted was $41\%/\sqrt{E}$), without the need of an additional constant term. The measurement of the e/h signal ratio yielded a preliminary value smaller than 1.1.

This is by far the best result ever obtained for a non-uranium hadron calorimeter. Two conclusions should be drawn from this remarkable success:

a) The emphasis on the crucial role of soft neutrons is correct. An effort to include these effects in the hadronic shower simulation codes is likely to pay off.

b) Hadron calorimetry is becoming a mature scientific activity, since the model calculations have predictive power. Using the experimental results by Kötz *et al.* as a starting point and Wigmans' calculations as a guideline, one can for example make a dedicated effort to optimize compensating lead-scintillator calorimeters.

We will show that it is likely that one can build a lead calorimeter with an energy resolution that is equally good as or better than the resolution of the HELIOS uranium calorimeter. The benefits of our design make it potentially superior in many respects. In our opinion, the fact that one could avoid the use of uranium would in itself already justify a serious R & D effort in this direction. Uranium has many disadvantages, amongst which we mention the radioactivity (handling, radiation damage, noise increase), the nasty mechanical properties, the limited availability (long delivery times) and last but not least the costs involved. At TeV energies uranium looses in addition one of its main advantages, *i.e.* the availability of a constant permanent calibration signal, because of dynamic range considerations. By using lead instead of uranium one would avoid spending a major fraction of an experimental budget on the processing of passive material.

In section 2 we will discuss the optimization of compensating lead-scintillator calorimeters. In section 3 we describe the detector that we have in mind and in section 4 the test program for a prototype. In section 5 we will make remarks on how to proceed and section 6 contains a summary.

2. OPTIMIZATION OF COMPENSATING LEAD-SCINTILLATOR HADRON CALORIMETERS

The energy resolution σ/E of a hadron calorimeter can be written as the sum of two terms[9] :

$$\frac{\sigma}{E} = \sqrt{\frac{a_0^2 + a_1^2 \times t}{E}} + b$$

The first term improves the energy resolution at increasing energy like $E^{-1/2}$. It consists of two components. The first component is the intrinsic energy resolution, dominated by the effects of nuclear binding energy losses; $a_0 = 0.24$ for lead. The second component is due to sampling fluctuations, t is the thickness of a single sampling layer. The constant term b contains a major contribution that depends on e/h, which vanishes for a compensating calorimeter. Other contributions to this term come from detector imperfections (stability, calibration errors, non-uniformities, etc.). The HELIOS experience has shown that these can be kept at the 1% level[5] for a uranium calorimeter. Similar values have been reported by UA2 for a non-radioactive calorimeter, where the performance was monitored by means of a system of lightflashers and external radioactive sources[11] . The contribution due to the sampling fluctuations has been estimated by Fabjan as[1] : $\sigma_{\text{sampling}}/E = 0.09\,\sqrt{\Delta E(\text{MeV})/E(\text{GeV})}$, where ΔE is the energy loss in a single sampling layer. For 10 mm lead plates ($\Delta E = 12.8\,\text{MeV}$) this gives $32\%/\sqrt{E}$ as the contribution of sampling fluctuations. The experimental result by Kötz *et al.* ($43\%/\sqrt{E}$) is, therefore, largely dominated by these sampling fluctuations, a consequence of the thick lead plates that they used. This means that the *total* energy resolution will considerably improve if one could use thinner lead plates. This is illustrated in fig. 1. The total energy resolution would be improved to $38\%/\sqrt{E}$ for 8 mm lead plates, down to $29\%/\sqrt{E}$ for 2 mm lead plates. For plate thicknesses less than 4 mm the intrinsic resolution would be the dominant contribution. To obtain such good values, the thickness of the scintillator plates would have to be scaled down proportionally since the thickness ratio should be kept at the value 4 to 1.

Figure 1 also shows how the electromagnetic energy resolution varies as a function of the lead plate thickness. Since sampling fluctuations are in this case the dominant component, the relative improvement is here even larger, from 27% (10 mm lead) to 12% (2 mm lead) at 1 GeV, for sandwich structures.

The optical properties of scintillator plates are such that thicknesses below 2 mm are unacceptable. The problems arising are mainly due to light attenuation. A typical transverse cell size of a sandwich scintillator calorimeter with wave length shifter readout is $20 \times 20\,\text{cm}^2$, which means that scintillation light has to travel on average approximately 15 cm before it reaches the wave length shifter (WLS) bar. If the light attenuation length becomes comparable to this distance, large lateral inhomogeneities will be introduced: the signal will strongly depend on the position of the impact point and the angle of incidence of the particle. Figure 2 shows the signal from a pointlike light source as a function of the source position relative to the WLS plates, for various values of the attenuation length (λ_{att}). A typical value of λ_{att} is 40 cm for 2.5 mm thick scintillator plates. If we assume that the light attenuation in thin plates is mainly due to surface effects, the attenuation length will be proportional to the plate thickness, which is roughly in agreement with experimental findings.

Figure 2 shows that the variations in the signal from the point source will be 7% for 2.5 mm plates, 47% at 1 mm and more than a factor of three at 0.5 mm. The light output integrated over the total scintillator volume is also considerably reduced for thin plates (the vertical scale is normalized).

In practice, for a single incident particle, the situation will not be as bad as suggested by fig. 2, since the transverse shower profile should be convoluted with these curves in order to estimate the real effects, but it is clear that if one aims for measurements at the few percent precision level, the curves for the thin plates are unacceptable, especially for the narrow electromagnetic showers. Hadron-induced showers at high energy also have a narrow transverse profile and will, therefore, similarly suffer from lateral inhomogeneities. The π^0 component in the shower development produces an intense central core[12] .

For isolated single particles one might hope to be able to correct somewhat for these lateral inhomogeneities, with the help of tracking information from upstream detectors, and the left-right light sharing. If several particles of different energies enter the calorimeter nearby each other, as is the case for jets, corrections for lateral light attenuation can not be made even if the position of each particle's impact point is known.

Thin absorber and scintillator material *can* be applied when using scintillating plastic fibres, whose optical transmission properties are much better than for slabs, and depend only weakly on their diameter (usual range 0.5 – 2 mm). Attenuation lengths of 1.5 – 2 m have been reported for 1 mm and even 0.5 mm thick coated polystyrene fibres doped with PBD and POPOP[13] . Such fibres were developed in Saclay[14] , initially for calorimetry[15,16] . The fibres are now mostly produced by a private firm[17] , licensed by Saclay. Also a Japanese company offers scintillating fibres, of comparable quality[18] . Scintillating plastic fibres have already found various applications in high energy physics experiments. We base our proposal to use fibres as active medium in *hadron* calorimeters on the experience with existing and planned *electromagnetic* calorimeters made of fibres embedded in lead[13] . Six experiments have successfully used the Omega Inner Calorimeter which was installed in 1984. The NA38 electromagnetic calorimeter has performed well, and the prototype of the DELPHI Small Angle Tagger has been successfully tested. In these detectors, the fibres run almost parallel to the direction of the measured γ's and e's, and are read out from the downstream end by phototubes or vacuum phototriodes. The lead to scintillator volume ratio is of order 1 to 1. The first two calorimeters have each fibre glued in grooved lead plates and hence are fully surrounded by lead, with a particularly small sampling thickness. They are modest in size (50 l for Omega, 5 l for NA38), and the production was only partially automatized. The accuracy is not the ideal one, mainly because of fibre inhomogeneities.

In the applications discussed above, 'blue' fibres were used. These offer the highest light yield, approximately 5 photoelectrons per minimum ionizing particle and per mm scintillator material. It is easy to dope the fibres with chemicals that shift the emitted light to the green (500 nm). This has the advantage of much larger attenuation lengths (up to 20 m) and of better radiation resistivity[19] . In particular the dopant 3-hydroxyflavone has interesting properties. It has a quantum efficiency of 0.36, a decay constant of less than 1 nsec, and virtually no overlap between the absorption and emission spectra[20] . There is more than enough light for calorimeter applications so this dopant seems particularly well suited for use in hadron calorimeters.

In order to obtain a compensating lead-scintillator hadron calorimeter, the lead to fibre volume ratio should be 4 to 1, which means that 20% of the detector volume is then occupied by fibres. If 1 mm fibres are used, approximately 250 km of fibre are needed per m^3 of detector, which we therefore call the Spaghetti Calorimeter. The contribution of sampling fluctuations to the energy resolution was computed to be some 30% smaller than for a 4 mm lead, 1 mm scintillator sandwich device, if each fibre is uniformly surrounded by lead[13] . Therefore, one might realistically expect to achieve an energy resolution $\sigma/E \approx 30\%/\sqrt{E}$ for hadron detection and $\sigma/E \approx 15\%/\sqrt{E}$ for electromagnetic showers.

3. THE SPAGHETTI CALORIMETER AND ITS ADVANTAGES.

Apart from the advantages offered by a compensating calorimeter with excellent energy resolution that were discussed in section 1, the spaghetti concept also eliminates what is considered one of the main disadvantages of sandwich scintillator calorimeters, namely the poor position resolution. The fibre concept essentially allows one to choose any granularity one likes (and can afford), since one is free to connect any number of fibres to a readout element.

Other major advantages are obtained if the fibres are running longitudinally, *i.e.* roughly in the direction of the particles that have to be detected (fig. 3). First of all, one avoids in this way the dead space taken by WLS bars and module covers in a sandwich structure, which is for example 8% of the total active volume in the case of the HELIOS detector. Secondly, one can avoid the lateral inhomogeneities in light yield discussed in the previous section. The performance of a hadron calorimeter is usually tested with a hadron beam which is sent into the stack at a given point. The σ of the measured signal distribution is interpreted as the energy resolution. Since the beam enters the detector always at the same impact point, the effects of lateral inhomogeneities introduced by light attenuation in the scintillator and by dead space are, on an average, the same for each event. The lateral inhomogeneities due to light attenuation in the scintillator and to dead space worsen significantly the energy accurracy with which secondary particles, entering at random and at not well known impact points can be measured. HELIOS tried to evaluate this effect by measuring the signal distribution of reaction products created by particles interacting in a thin target ("jet" energy resolution)[5] . For 200 GeV pions this jet resolution was found to be approximately twice the beam particle value ($\sigma/E = 5\%$ versus 2.5%) which is not surprising given the dead space and the attenuation length.

Such effects, which will clearly limit the high energy performance of sandwich type scintillator calorimeters, are absent in the spaghetti case. On the other hand, fluctuations in longitudinal shower development, in combination with light attenuation in the fibres will contribute to the energy resolution. Light attenuation in the fibres can affect the calorimeter resolution in two ways:

a) The attenuation lengths for different (sets of) fibres usually vary. The resulting fluctuations in the fibre-to-fibre response to a given light pulse will be most important near the open end, *i.e.* where most of the light is produced in a shower that develops in an unsegmented calorimeter. The effects of this can be particularly important in electromagnetic showers, where a substantial fraction of the total energy is deposited in a limited number of fibres. A hadron shower is less sensitive to these effects, because the energy is usually shared by a much larger number of fibres. In general, one can eliminate these effects by keeping the fibre length small compared to the (average) attenuation length, and/or by selecting the fibres that are grouped into one electronic channel in such a way that the channel-to-channel fluctuations in $< \lambda_{att} >$ are small.

b) The depth profile of the light production varies from shower to shower, and therefore the resulting signal is affected by the light attenuation in the fibres. The fluctuations resulting from this effect will be much more important for hadronic showers than for electromagnetic ones. In the latter case, the scale for variations in the longitudinal shower development is set by the effective radiation length, for hadronic showers by the effective nuclear absorption length λ_{abs} of the calorimeter. This scale factor corresponds to the width of the distribution of the depth at which the shower starts developing, and leads in first approximation to a constant term in the energy resolution for single particle detection of the order of $\lambda_{abs}/\lambda_{att}$. For detection of jets this term can be considerably smaller, depending on the number of particles in the jet and their energy distribution, because several showers develop independently in this case.

Both types of effects become small for a large (average) light attenuation length. For a hadron calorimeter large means large compared to the effective nuclear absorption length. For a compensating lead/plastic-scintillator combination, λ_{abs} amounts to 20 cm, whereas λ_{att} may be many meters.

We do not expect any significant contribution of longitudinal inhomogeneities to the energy resolution of the proposed calorimeter. This can be concluded from the fact that both ZEUS and HELIOS measured excellent energy resolutions for high energy pion beams, in spite of the fact that their WLS bars had an attenuation length $< 1.5\,\mathrm{m}$[5,21] . Light attenuation in these bars should produce effects of the same type as discussed here for fibres. In these experiments, the open end of the WLS bars was equipped with a reflecting mirror. This made the response curve of the WLS bar as a function of depth much flatter than $\exp(-\lambda_{\mathrm{att}})$. The same trick may be applied for the fibres. Especially the green fibres mentioned in the previous section will, therefore, certainly have an attenuation length that is sufficiently large to make this source of fluctuations of negligible importance, even for unsegmented calorimeters.

Summarizing this point, we conclude that there is reason to believe that the jet energy resolution will be similar to the single beam particle energy resolution for the compensating lead-based spaghetti calorimeter, and that its constant term can be limited to the 1% level.

The fact that no separate WLS bars are needed in the spaghetti calorimeter leads to an important gain of light, about an order of magnitude. From existing experience one may expect several hundred photoelectrons per GeV for PM readout. This light yield might be sufficient to use semiconductor elements (photodiodes) for readout, or vacuum phototriodes (VPT). This would have the following advantages. First, such elements are intrinsically more stable than photomultipliers, which is important in view of the problems related to calibration and stability that any detector producing light signals faces. Second, there would be less problems to operate in a magnetic field. Third, this type of readout would require less space than photomultipliers. Clearly, the possibility of using such readout elements is closely linked to the granularity and the gate time that can be accepted. A systematic study of the possibilities and limitations in this respect should obviously be an important part of an R & D project.

Last but not least, the spaghetti calorimeter offers anyhow advantages with respect to the calibration. High precision calorimetry requires usually a major effort on the energy calibration of the system. In particular with optical readout, the associated problems are in general non-trivial to solve. Two aspects are important for obtaining a satisfactory result:

a) Tuning the gain of the readout elements such that a given particle always produces the same signal (measured in Coulombs) independent of the calorimeter channels in which it is detected (relative calibration).

b) Setting the absolute energy scale (absolute calibration).

The latter can, for example, be achieved with an electron beam that is sent into a few modules. The first aspect, which needs regular rechecking and eventually adjustment, requires a different method, in particular for a system with many thousands of electronic channels. It is of crucial importance that in this procedure the complete optical chain be tested, *i.e.* the scintillation process, the light transmission, the optical coupling between the various components, and the characteristics of the readout device and the ADC. Radioactive sources make this possible in a convenient way. However, the gammas from such sources do not reach very far. External sources like ^{60}Co, therefore, only generate light in the first $\approx 0.3\lambda_{abs}$ of the detector. For sandwich structures with WLS readout this implies that the results are extremely sensitive to peculiarities of the first few scintillator plates, *e.g.* anomalies in the plate thicknesses or in the coupling to the WLS plates. The experience by ZEUS has learned that this makes calibration results obtained in this way rather unreliable[10] . This will be totally different for the spaghetti calorimeter. An external source placed upstream will generate scintillation light in *all* the fibres and, therefore, allows to test the complete sensitive medium. In combination with measurements of signals from a downstream source, the time evolution of the attenuation lengths may be monitored. We expect to be able to obtain reliable calibration results with this method.

The fibres should run roughly, but not exactly, in the direction of the particles that one wants to detect. "Channelling" effects where the particle travels a long distance inside one individual fibre, should be avoided. Such effects have been observed to slightly deteriorate the energy resolution for electromagnetic showers, at very small angles of incidence (DELPHI). In OMEGA one successfully used wiggling fibre paths to eliminate the problem. It is probably easier to construct the detector in such a way that the particles can never enter it under zero degrees with the fibre direction.

A generalized use of fibre calorimetry will probably also require some longitudinal granularity. Very interesting possibilities are opened up if one would build the spaghetti calorimeter with a (quasi-)pointing geometry (fig. 4). In order to keep the volume ratio lead to fibre about constant, one would have to start new series of fibres at various depths inside the detector. This then automatically provides a longitudinal segmentation with possibilities for particle identification (electron/hadron separation) without having to physically split the detector into separate sections. This would make possible the construction of an extremely compact detector. We already mentioned the fact that the effective nuclear absorption length of the proposed detector amounts to $\approx 20\,\text{cm}$. This makes the lead-based spaghetti calorimeter one of the most compact devices that one can realistically imagine. Note that a compensating uranium/plastic-scintillator detector also has an effective nuclear absorption length of 20 cm.

The possibilities of using a (quasi-)pointing geometry depend among others on the distance to the interaction point at which the calorimeter has to operate. It should be said, however, that the calibration will be more difficult for such a geometry.

4. A TEST PROGRAM FOR A PROTOTYPE

The R & D program to test these ideas should consist of two main phases. In Phase 1 a very simple geometry should be used, namely a rectangular one, with a size sufficient to contain a hadron shower of a few hundred GeV at the 99% level. Leakage should be small enough so that its fluctuations do not affect the energy resolution.

For a lead-scintillator calorimeter the size should typically be $1 \times 1 \times 2\,\mathrm{m}^3$. The 2 m long fibres are homogeneously distributed and are running parallel to each other. For 1 mm fibres the distance between the centres of neighbouring ones amounts to approximately 2 mm (see fig. 5). In this phase of the program the following topics should be studied:

i) Energy resolution for electrons and pions for normally incident particles, e/h signal ratio, signal linearity. Separation of the contribution of the sampling fluctuations to the energy resolution from the contribution due to intrinsic fluctuations.

ii) The effect of variations of ± 1 unit in the volume ratio lead to fibre, in view of the small variations that will have to occur in the case of a (quasi-)pointing geometry.

iii) Transverse shower development and electron/muon/hadron discrimination on the basis of this information.

iv) The signal as a function of the angle of incidence.

v) The readout. Applicability of semiconductor or VPT readout. Limitations on granularity and gate time.

vi) Calibration and stability.

In addition, we want to study some of the problems that come up if the detector is split into separate longitudinal modules (calibration, readout). We will build a small ($40 \times 40 \times 20\,\mathrm{cm}^3$) module with the same structure for this purpose. This module can serve as electromagnetic section for tests in a particle beam.

We propose to use sheets of lead with grooves of 1 mm (fig. 6). A similar technique has given satisfactory results in practice, for the small electromagnetic calorimeters mentioned before. Large sheets of lead are very hard to handle and to machine in this way, because of the mechanical properties of lead. The SLD Collaboration, however, have developed together with industry a lead alloy (lead plus 0.065% Ca, 1.15% Sn) with excellent mechanical properties. It is very stiff and easy to machine. The proposed structure will allow to vary the volume ratio lead to scintillator by adding thin lead foils in between two grooved sheets. Concerning this point, one could also imagine a stage zero, in which the sensitivity of the calorimeter performance to the sampling fraction is investigated with a sandwich structure, by rebuilding existing modules (e.g. the ZEUS prototype). In this way it would become possible to make a reliable design for the more complicated mechanical structure of the spaghetti detector in an early stage of the project.

The results obtained in this first phase should provide crucial information needed before moving on to Phase 2, which consists of the exploration of the possibilities of a (quasi-)pointing geometry and/or multiple longitudinal readout (3-D granularity). In that phase one should study the possibility of electron, hadron and muon identification from the longitudinal energy deposition and measure the jet energy resolution.

5. HOW TO PROCEED?

We have already referred to a phasing of the proposed R & D program. Phase 1 concerns the design, construction and testing of a calorimeter with rectangular geometry, while Phase 2 would involve the design, construction and testing of a prototype calorimeter with a more flexible geometry. We would like to start with a modest Phase 0 that allows us to answer in the very short term some crucial questions which are basic to the selection of lead and scintillator as the materials of choice for the proposed spaghetti calorimeter.

So far only two lead-scintillator sandwich structures have been tested, both by the ZEUS Collaboration. One is the compensating calorimeter discussed earlier[10] (10 mm lead plates and 2.5 mm scintillator plates), the other a non-compensating calorimeter[22] (a mixture of 4 and 5 mm lead plates and 5 mm scintillator plates). It is clearly desirable to perform measurements for a few other sampling fractions as soon as possible, to prove that our understanding of the underlaying physics issues is good enough to predict the optimal sampling fraction for the Phase 1 design. As a byproduct we would attempt to separate the contributions of the sampling fluctuations (a_1, *cf.* formula on page 5) from the intrinsic energy resolution (a_0), for example by blocking the light coupling to the wavelength shifter of every second scintillator layer. The intrinsic resolution is the ultimate limit that can be reached and it is of great interest to verify that it is for lead at the level indicated in fig. 1. We can achieve these goals in a timely way by introducing a Phase 0 as follows.

The existing test calorimeter of Kötz *et al.*, including mechnical stand, associated readout electronics, computer and testbeam facilities can in principle be used to obtain results this summer. This calorimeter consists of 2.5 mm scintillator plates sandwiched between 10 mm leadplates for a total of 5 nuclear absorption lengths. The transverse dimensions are $60 \times 60\,\mathrm{cm}^2$. The detector is read out by means of wavelength shifters, after 1 and 5 absorption lengths, respectively. To vary the sampling fraction additional lead plates are needed, with thicknesses sufficiently different from the existing 10 mm plates. The most economical solution is to order 7 mm plates and use these to obtain 7 and 14 mm sampling geometries. After an initial test of the 10 mm geometry, the test modules would be restacked using the other lead plates. Restacking can be done in about 3 days each time. In order to keep the number of absorption lengths the same for each sampling fraction that is tested, the number of scintillator plates to be read out should vary with the sampling fraction.

A few days of running in a test beam would yield a wealth of information. The software required for the data analysis is already available from previous tests. The manpower requirements for Phase 0 are ≈ 0.5 man-year of technical help, mostly for restacking the calorimeter. Moreover, 1 man-year is required for the supervision of the project during Phase 0. Two of us (H.P.P. and R.W.) are prepared to work on this starting this summer, the other authors have commitments through this calender year and can start early 1988. This part of the project will be a joint effort with ZEUS.

In parallel with the Phase 0 work we would investigate various methods for mass production of lead plates for the rectangular geometry and the assembly of a large number of such plates with the very large number of delicate scintillating fibres required. This is essentially a mechanical problem. Some methods should be tried out on a small scale with the help of the CERN (or other) mechanical workshops in Fall 1987. In addition we want to test in the laboratory a number of possible readout schemes such as diodes, vacuum triodes or tetrodes, and low gain photomultipliers.

We have made a conceptual design for a Phase 1 test module of $108 \times 108\,\mathrm{cm}^2$ transverse dimensions and 2 m depth. These dimensions correspond to 5.5 nuclear absorption lengths in the transverse direction and 10 in the longitudinal one. They are chosen such as to insure at least 99% containment for the highest energy hadron beams available at CERN. In order to reduce the required number of readout channels without limiting in any way the test program outlined in section 4, the design foresees a gradual increase in transverse segmentation of the readout. This variation in segmentation is achieved by adequately grouping the fibres for readout. Near the impact point of the testbeam the cellsize is $1\times1\,\mathrm{cm}^2$ increasing to $3\times3\,\mathrm{cm}^2$ and so on, up to $12\times12\,\mathrm{cm}^2$ near the edge. This is shown in fig. 7. The total weight is 21.7 ton, the number of fibres is approximately 300,000 (total length 600 km) while the number of readout channels is 149. The calibration will be done with a ^{60}Co source, that scans the front face of the detector under remote control. The calibration results will be checked with particle beams.

The module should be ready for testing with low energy beams from the PS starting Fall 1988. The definitive tests, which require high energy beams from the SPS, should take place in Summer 1989. The materials cost of Phase 1 is estimated to be approximately 2.0 MSFr consisting of 1.3 MSFr for the calorimeter including the fibres, approximately 0.4 MSFr for electronics, and approximately 0.3 MSFr for contingency. The contingency is calculated to be approximately 30% of the materials budget, excluding the cost of the fibres. We will know the considerable costs of the fibres accurately before the project moves forward. The manpower required is about 3.5 man-years of technical help and 2 man-years for supervision for a total cost of approximately 0.4 MSFr. We assume that the remotely controlled stand for the calorimeter and other test beam infrastructure of the UA2 test beam in the North Area will be available for free. Probably also some of the UA2 electronics and computer equipment can be used for our purpose. All above figures are rounded off, more precise estimates are given in the Appendix.

We prefer to delay the detailed proposal for Phase 2 to a later stage, when the results of Phases 0 and 1 can be evaluated. The specific design of the Phase 2 calorimeter will be affected by these results and, by then, also perhaps by the specific requirements of an experiment at a future supercollider.

6. SUMMARY

If the proposed ideas can be made to work as expected, we will have a calorimeter that

a) can measure single particles with an energy resolution $\sigma/E = 30\%/\sqrt{E}$ for hadrons and $15\%/\sqrt{E}$ for electrons.

b) has a jet energy resolution that beats all records and comes close to the 1 % level for jets of a few hundred GeV,

c) has no cracks,

d) can operate in a magnetic field,

e) is extremely compact ($10\,\lambda_{abs}$ in $2\,m$),

f) is rather radiation resistant (no problems below 1 MRad, a level that is never reached in over 90% of any detector foreseen at for example the LHC)

g) uses present-day technology,

h) is relatively easy to construct, and consequently

i) is relatively cheap.

Everybody would want such a detector. However, the timescale of the described R & D program needed to come to this point and the expertise needed to carry it out are probably such that it will be very hard to fit within the possibilities of a Collaboration proposing an experiment. This is clearly demonstrated if one analyzes the R & D effort that has gone into the calorimeter designs of SLD, D0, UA1, ZEUS etc.

Although the required technology exists at present, the scale of the project demands that considerable ingenuity and work be devoted to automation of the construction procedure and to an automatic quality control of the large amount of fibre that has to be handled.

Therefore, it is our feeling that this R & D program should get the status of a separate project, not being directly linked to a specific experiment. The results of this project will be important for any experiment at future high-energy machines, and probably also for upgrades of experiments that are currently running or are being prepared at accelerators like LEP, Tevatron and SLC. This is of course our motivation. Other physicists (with plans to get) involved in such experiments, and in particular those having relevant experience, should of course be welcome to join and help us. Efforts to extend the group of people that will actively contribute to the project are underway.

In order to be successful, this project would need to have a status comparable to an approved experiment. It would need an adequate budget and access to the CERN infrastructure, *e.g.* beam time.

Because of these considerations it would, in our opinion, perfectly fit into the new detector R & D program (LAA project) that the CERN Council has recently approved.

REFERENCES

1) See for example C.W. Fabjan and T. Ludlam, Calorimetry in High-Energy Physics, Ann. Rev. Nucl. Part. Sci. **32** (1982) 335.

2) Large Hadron Collider in the LEP Tunnel. Proceedings of the ECFA-CERN Workshop, Lausanne (1984), CERN 84-10.

3) C.W. Fabjan and W.J. Willis, in Proceedings of the Calorimeter Workshop, Batavia Illinois (1975), p. 1, M. Atac, ed.

4) T. Akesson *et al.* Nucl. Instr. and Meth. **A241** (1985) 17.

5) T. Akesson *et al.*, Performance of the Uranium/Plastic Scintilator Calorimeter for the HELIOS Experiment at CERN, CERN preprint (1987), to be published.

6) See for example H. Abramowicz *et al.*, Nucl. Instr. and Meth. **180** (1981) 429.

7) M. de Vincenzi *et al.*, Nucl. Instr. and Meth. **A243** (1986) 348.

8) H. Brückmann and H. Kowalski, The Dependence of Calorimeter Responses on the Gate Width, DESY, Hamburg, ZEUS Internal Note 86 / 026 (1986).

9) R. Wigmans, On the Energy Resolution of Uranium and Other Hadron Calorimeters, CERN-EP/86-141 (1986), to be published in Nucl. Instrum. and Meth.

10) U. Kötz *et al.*, private communication.
R. Klanner, Test Results for the ZEUS Calorimeter, Contribution to the International Conference on Advances in Experimental Methods for Colliding Beam Physics, SLAC, March 1987.

11) A. Beer *et. al.*, Nucl. Instr. and Meth. **A224** (1984) 360.

12) C. Leroy, Y. Sirois and R. Wigmans, Nucl. Instr. and Meth. **A252** (1986) 4.

13) P. Sonderegger, Fibre Calorimeters: dense, fast, radiation resistant, CERN-EP/86-214.

14) L. Allemand *et al.*, Nucl. Instr. and Meth. **A225** (1984) 522.

15) H. Burmeister *et al.*, Nucl. Instr. and Meth. **A225** (1984) 530.

16) H. Blumenfeld and M. Bourdinaud, Scintillating fibers for calorimetry, Yellow report CERN 85-10 (1985) 249.

17) Optectron, Z.A. Courteboeuf, B.P. 535, Av. du Quebec, F-91946 Les Ulis, France

18) Kyowa Gas Chemical Company; M. Gilchriese, private communication

19) J. Kirkby, Today and Tomorrow for Scintillating Fibre Detectors, CERN-EP/87-60, and references therein.

20) C.L. Renschler and L.A. Harrah, Nucl. Instr. and Meth. **A235** (1985) 41.

21) Y. Sirois and R. Wigmans, Nucl. Instr. and Meth. **A240** (1985) 262.

22) C. Daum *et. al.*, Description and First Results of a Hadron Test Calorimeter for ZEUS, DESY, Hamburg, ZEUS internal note 86/13 (1986).
J. Engelen, H. Tiecke, Test Calorimeter for the ZEUS Experiment, preprint NIKHEF-H/86-18 (1986).

FIGURE CAPTIONS

1. The energy resolution of a compensating lead-scintillator calorimeter as a function of the thickness of the lead plates.

2. Effect of the light attenuatiuon length of the plastic scintillator on the response of a sandwich type calorimeter to a point light source. The horizontal scale gives the position of the source with respect to the wave length shifter plates. A $20 \times 20\,\mathrm{cm}^2$ transverse cell size is assumed.

3. Orientation of the fibres in the spaghetti calorimeter.

4. Schematic layout of a spaghetti calorimeter module with quasi-pointing geometry.

5. Lateral cross section of the compensating spaghetti hadron calorimeter.

6. Longitudinal cross section of the compensating spaghetti hadron calorimeter.

7. The transverse segmentation of the Phase 1 test calorimeter.

APPENDIX

Phase 0 Budget

Materials costs

Mechanical

lead plates @ 5 SFr/kg	18	kSFr		
magnetic tapes 100 @ 20 SFr/tape	2			
various (paper, tools)	10			
contingency	15			
total mechanical			45	kSFr

Electronics	nil			
Total materials			45	kSFr

Personnel costs

technical 0.5 man-year @ 60 kSFr/man-year	30	kSFr		
physicist 1 man-year @ 110 kSFr/man-year	110			
Total personnel			140	kSFr

Total Phase 0 costs are 185 kSFr

Phase 1 Budget

Materials costs

Mechanical

lead including cutting @ 5 SFr/kg	106	kSFr		
lead grooving @ 2 SFr/kg	42			
scintillating fibres @ 1.4 SFr/m	978			
module mechanics	150			
remotely controlled radioactive source	40			
contingency	169			
total mechanical			1485	kSFr

Electronics

photomultipliers (or other) @ 300 SFr/ch	60	kSFr		
bases @ 200 SFr/ch	40			
high voltage @ 400 SFr/ch	80			
ADCs @ 185 SFr/ch	37			
source controller	30			
CAMAC	20			
computer, tapes	100			
contingency	184			
total electronics			550	
Total materials			2035	kSFr

Personnel costs

Technical

lead plate production	1	man-year			
fibre assembly	2				
overall assembly	0.5				
total	3.5	man-year	@ 60kSFr/man-year	210	kSFr

Supervision

physicist	2	man-year	@ 110kSFr/man-year	220	
Total personnel				430	kSFr

Total Phase 1 costs are 2465 kSFr

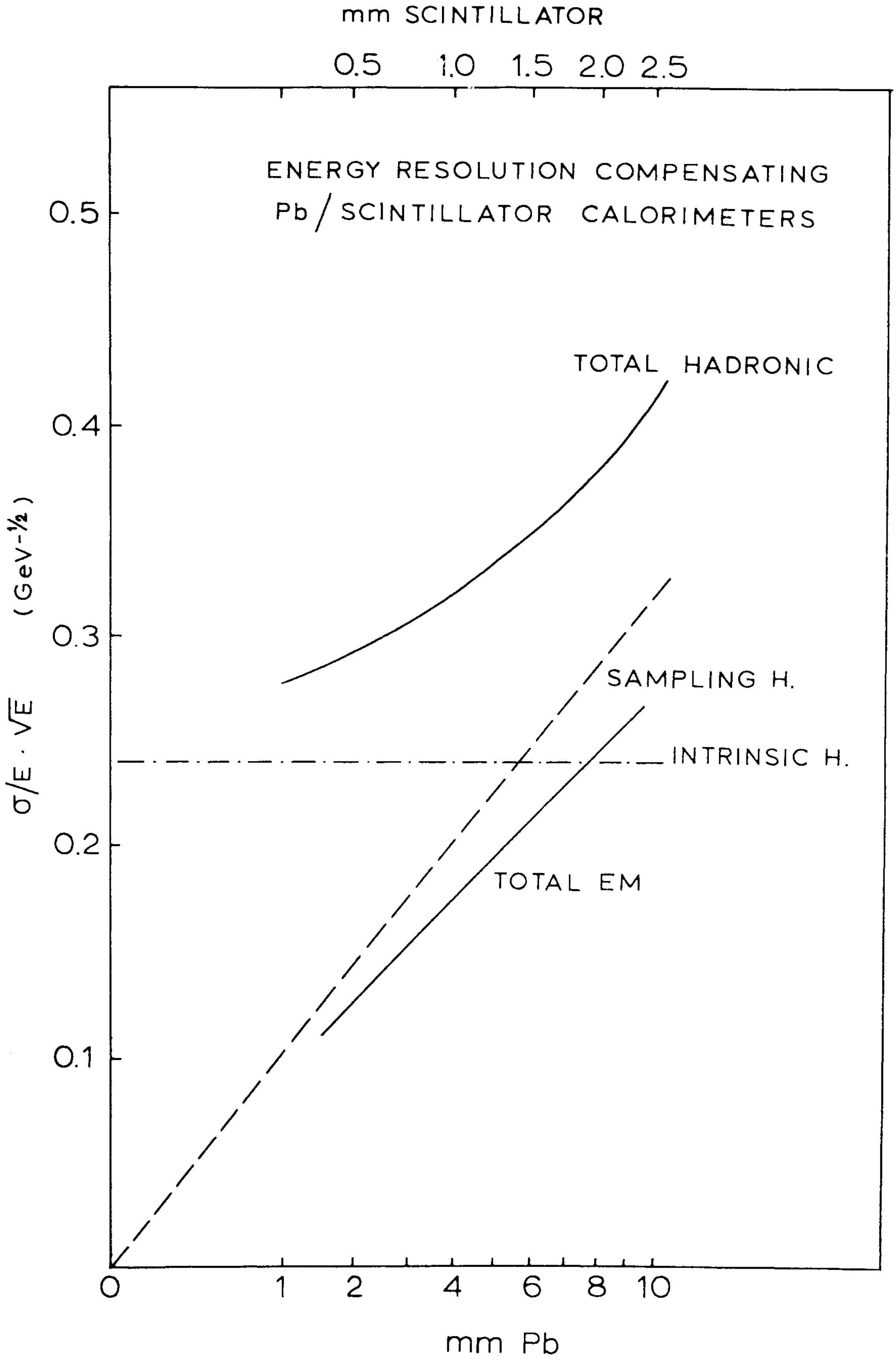
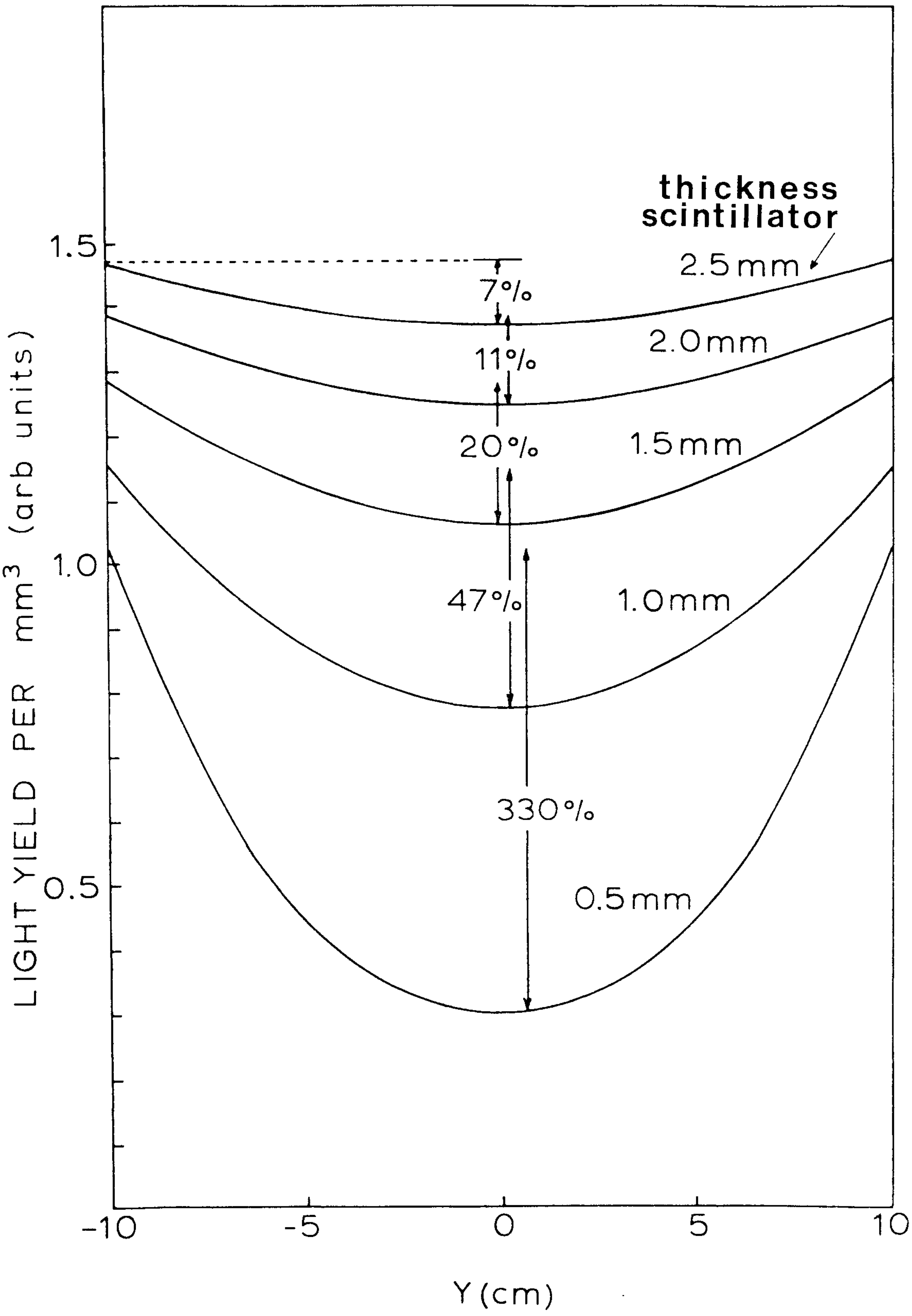

mm SCINTILLATOR
0.5
1.0
1.5
2.0
2.5
ENERGY RESOLUTION COMPENSATING
Pb / SCINTILLATOR CALORIMETERS
TOTAL HADRONIC
SAMPLING H.
INTRINSIC H.
TOTAL EM
σ/E · √E (GeV^-½)
0.5
0.4
0.3
0.2
0.1
0
1
2
4
6
8
10
mm Pb

FIGURE 1



thickness
scintillator
2.5 mm
2.0 mm
1.5 mm
1.0 mm
0.5 mm
7%
11%
20%
47%
330%
1.5
1.0
0.5
LIGHT YIELD PER mm^3 (arb units)
-10
-5
0
5
10
Y (cm)

FIGURE 2

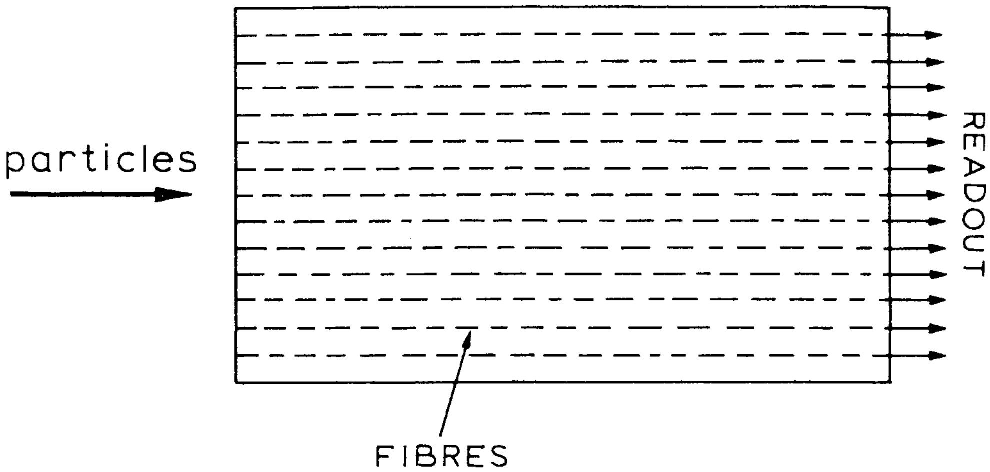


FIGURE 3

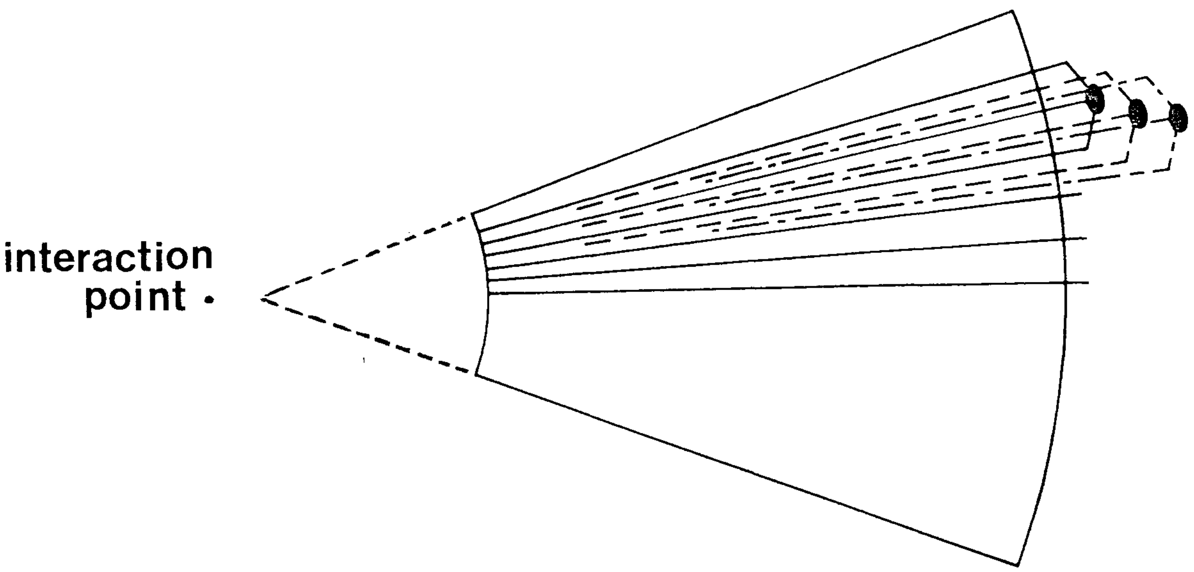


FIGURE 4

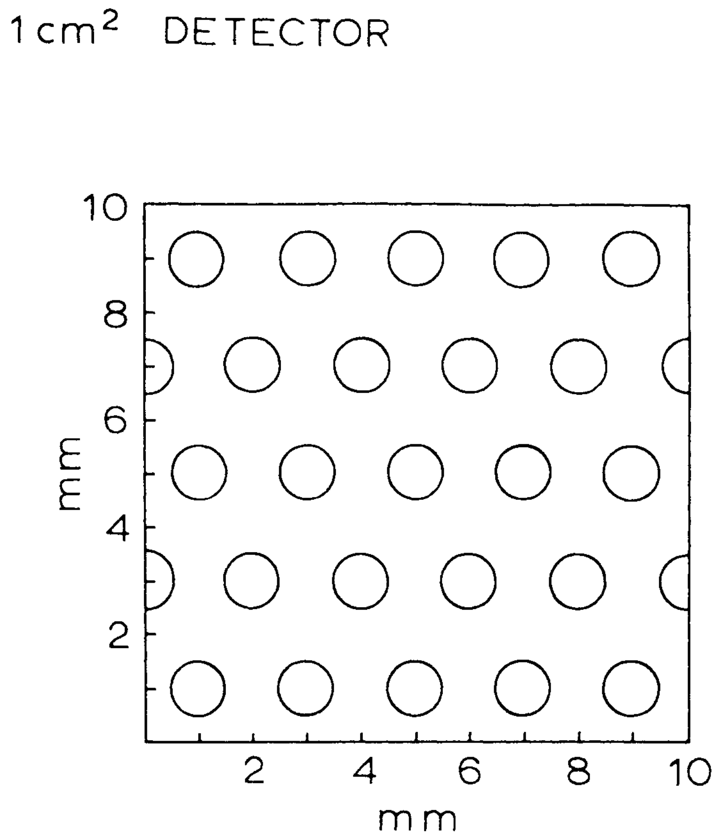


FIGURE 5

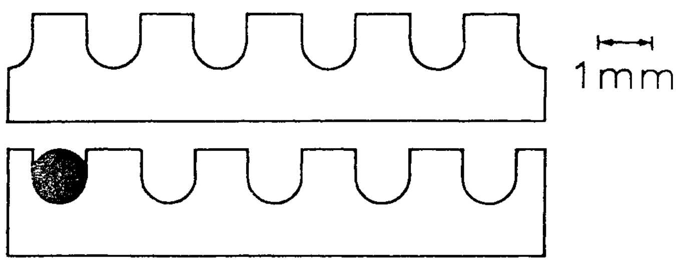


FIGURE 6

Grouping of Fibres into Lateral Cells

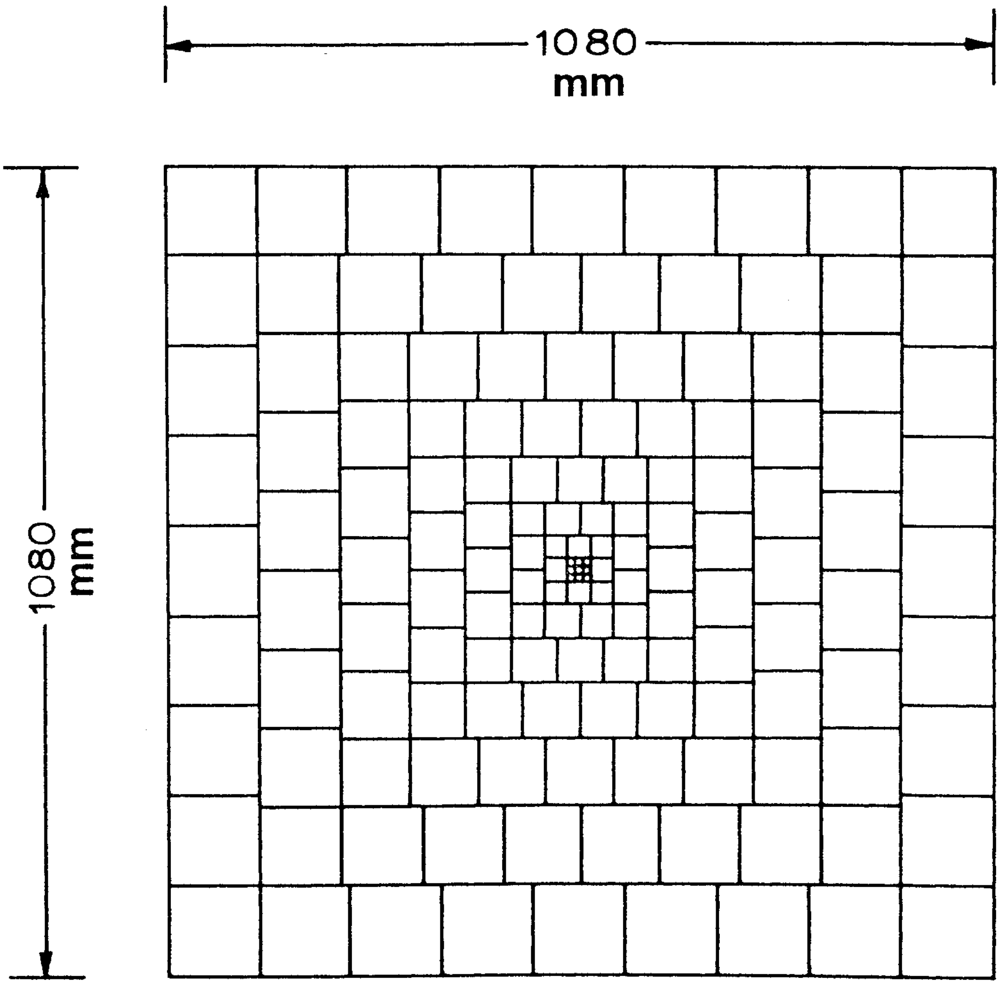


FIGURE 7

1 3 MARS 1991