HIGH-RESOLUTION LOW-COST PHOTON DETECTORS FOR LARGE ASSEMBLIES

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Abstract:

Prototype modules for a multicell system of shower detectors, detecting electrons or photons and measuring their energy, have been studied in the 0.25 - 10 GeV range. Each cell is made of a sandwich of thin layers of lead and scintillator, the produced light being extracted by acrylic rods or plates doped with a wave-length shifter (BBQ). Extensive tests led to a simple, low-cost and compact module using two extraction plates and allowing measurement of energy ($\sigma \approx 9\% \sqrt{E}$) and position ($\sigma \approx 15$ mm) of the electromagnetic shower. A system of square cells seen by four converter plates is proposed for a CERN SPS experiment.

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1. INTRODUCTION

With the advent of very high energy accelerators and colliders, the identification and energy measurement of electrons or photons by calorimetry has become one of the most powerful techniques available to particle physicists. Up to now, total absorption detectors, such as NaI or Pb-glass, were often preferred for their good energy resolution and for the facility in building large hodoscopes with small efficiency losses. Nevertheless, lead-scintillator sandwiches [1,2] have been used extensively in the past twenty years when the ultimate energy resolution was not required. Their cost is relatively low and their construction easy if the number of scintillator plates, light-guides and phototubes is kept small. The energy resolution is then limited by the poor sampling frequency. Moreover, classical light-guides make difficult the construction of large assemblies with minimal losses in sensitive area.

The possibility to extract some of the light produced in a scintillator, using acrylic plates or rods doped with a wave-length shifter and parallel to the particle direction, is very attractive for electromagnetic calorimeters, where the total amount of light available is large. A single plate or rod can then extract a fraction of the light produced in each scintillator and guide it to a photomultiplier located behind the detector. A fine sampling can be achieved easily, allowing energy resolutions comparable to those obtained with total absorption calorimeters to be reached.

The use of wave-length shifters in plexiglas to collect scintilla-

tor light and guide it to photomultipliers has been known for some time [3-6]. The principle of the method is illustrated in fig.1. The light coming out of the edge of each scintillator sheet crosses a small air gap and penetrates a converter bar. The near U.V. component of the light is absorbed, wave-shifted to larger wave-length (green light) and isotropically re-emitted. About $1/3$ of this light is then trapped in the bar and can be guided to a photomultiplier. Surface ratios of 50-100 between scintillator edges and photocathodes can thus be achieved.

Many tests on materials and on prototypes based on this principle have been performed [7-14] and several such calorimeters are used in experiments. In these attempts, good energy resolutions are generally obtained, but large inhomogeneities are observed, when measurements of position dependence are reported; they are due to the short attenuation length of scintillators for U.V. light. Only the knowledge of the shower position allows correction of these effects.

Our aim is to study a compact modular e/γ calorimeter combining low-cost, simplicity of construction and operation with an energy resolution approaching that of lead-glass over a large sensitive area. Such a calorimeter may be used in a CERN SPS muon experiment (EMC/NA9) in regions where photons up to 10 GeV energy are expected; the angular resolution necessary for $\gamma\gamma$ invariant mass reconstruction leads to maximum cell sizes of the order of 10 to 20 cm, depending on the angular region considered. In a first series of tests, the possibility to use only one acrylic doped rod or plate for light extraction is studied with various scintillating materials. A second series of measurements is carried out on prototypes using a two-plate light extraction, which give very satisfactory results.

2. TEST CONDITIONS

2.1. Electron beams and set-up

Most of the measurements have been performed in the CERN PS neutral beam b_{16} . This beam, produced on an internal target at zero degrees with respect to the circulating protons, contains essentially neutrons and gamma rays with momenta up to ≈ 12 GeV/c. Relativistic protons are also available in special conditions.

The electrons produced in a thin lead converter (5 mm) are momentum analyzed in a two meter long bending magnet. The tested prototypes are placed at about 8 meters downstream of the magnet at an angle allowing to scan an energy range from .25 to 10 GeV by varying the current in the magnet. Two counters between the converter and the magnet, and a telescope of 3 counters between the magnet and the prototypes define the electron beam as shown in fig.2. The counter sizes result from a compromise between beam momentum spread and minimum useful rate. In order to determine the energy resolution of the detectors with negligible beam contribution, measurements were also done in the PS beam q_{12} , which is a classical charged particle beam operating up to 4 GeV/c.

2.2. Test prototypes

At the start of our study, we made the assumption based on published work [8-13], that acrylic rods or plates doped with the BBQ wave-length shifter (see Fig.3) make very suitable converters to extract the light from either vinyllic or acrylic scintillators.

The choice of the scintillator is guided by the partly conflicting requirements of large light output, fine sampling but compactness,

and cost. NE104b scintillator, which is the NE110 optimized for BBQ coupling, should give plenty of light and allow to work with thin plates of scintillator (2-3 mm). But, especially in these thicknesses, the cost is prohibitive for large assemblies. Plexipop coupled to BBQ converters gives, as reported in various publications, 4-5 times less light than NE110 or NE104b. Our first tests are to establish the possibility of using acrylic scintillator such as polymethylmetacrylate (PMMA), named Altustipe [15] or Peterglas [16], the price of which is of the same order as Plexipop. On the other hand, the optimum BBQ content in the converter has to be determined and a suitable photomultiplier to be found. The various optimisations and comparisons to be made and further tests on a two-plate light extraction system (fig.4), using a 'new' scintillator: polystyrene (PS) [18], led to the construction of the prototypes described in table 1.

The converter rods [17] are available for each diameter in four BBQ concentrations: 30, 90, 150 and 300 mg/l. They are 38 cm long, completely polished, and directly coupled to the photomultiplier with silicone grease optical contact. The converter plates [15] are made of 3mm thick plexiglas, doped with 90 mg/l BBQ and joined to the photomultipliers by a stripped light-guide. One face and the polished edges of the plate are covered with aluminized mylar. The scintillator plates are machined on the edges and depolished around the central hole or on the edge facing the converter plate. They are dressed in aluminized mylar, except for the PS plates. There is a ≈ 1 mm gap between the rod or plate and the scintillators.

3. MEASUREMENTS ON SINGLE-EXTRACTION PROTOTYPES

3.1. Linearity and energy resolution

These studies are made with prototype P_{20} , in which the 5 mm NE104b scintillator plates should make the photostatistics contribution to the energy resolution small. Measurements with converter rods of diameter 2, 1.5 and 1cm have shown that the light output is roughly proportional to the rod diameter. The 2cm diameter plexiglas rod used in P_{20} is doped with 90 mg/l of BBQ, which was found to be the optimum concentration. Several photomultipliers were tested; the EMI 9813 KB (2") and the Phillips XP 2008 (32mm) yield good linearity over a sufficient dynamic range. We chose the latter for its diameter well suited to the surface to view and its low cost. The following measurements are made with the electron beam hitting P_{20} at 5 cm from the central rod in order to minimize the effects of shower particles in the central rod and of lateral leaks.

Pulse height (PH) spectra for electrons of energy between .25 and 10 GeV are recorded for 3 sampling thicknesses: 1, 1.5 and 2mm of lead. Fig.5a shows the variation of the peak position (channel number after pedestal subtraction) and of the FWHM with electron energy. For 2mm of lead, a linearity better than 2% is observed. For 1.5 and 1mm, a saturation is seen as expected since the total material is not compensated (10 and 7RL respectively). Fig 5b shows the corresponding energy resolutions in regions where no saturation is observed. The improvement with decreasing sampling thickness is clearly seen at 1 GeV.

Since the beam energy spread gives some contribution to these resolutions, as will be seen in section 4.4, we can conclude that resolutions of the order of

$$\frac{\sigma}{E} \approx \frac{8\%}{\sqrt{E}}$$

can be achieved with 1 mm sampling thickness and a large amount of light collected. In fact, measurements with protons show that 2.2 photoelectrons (phe) are obtained from each scintillator plate of P₂₀; for 16eV electrons, ≈ 10 phe/plate are collected. If we add quadratically the contributions to the energy resolution expected from a 1mm lead sampling ($\approx 6\%$) and from photostatistics ($\approx 5.3\%$), a figure of $\approx 8\%$ is predicted.

3.2. Scintillator study

The light outputs of NE104b, Altustipe and Peterglas, measured with the proton beam onto prototypes P₁₁, P₁₂ and P₁₃, as a function of the distance d of the beam to the centre of the rod is shown in Fig.6. The point at $d=0$, common to the three modules, represents the light output for protons producing Cerenkov light in the rod. In fact, the size of the scan counter (1cm^2) allows, for $d=0.5\text{cm}$, to observe simultaneously the two peaks corresponding to the light produced in the edge of the scintillators or in the rod. The ratios $\text{PH}(d=1\text{cm})/\text{PH}(d=4\text{cm})$, given in table 2, show that the dependence with d is sharp for all scintillators tested with a small advantage to NE104b. The large dependence can be attributed to the combined effects of the very short attenuation length of the scintillators for the U.V. component of the emitted light and of the solid angle under which the light source sees the rod. We will discuss in section 3.3 attempts to decrease or overcome this effect.

In order to compare the light outputs, the PH for $d = 3, 4$ and 5cm are summed and normalized to the NE104b light yield (table 2). The

Altustipe PH is corrected for the different thickness of scintillator traversed by the protons. Taking into account the fact that the Peterglas sample has 15% naphthalene content against 10% for Altustipe, the light outputs are very similar. We conclude that PMMA scintillators, coupled to BBQ, yield $\approx 1/2$ of the light of NE104b (supposed to give 2-3 times more light than NE110 in these conditions) and that they represent a low-cost (same order as Plexipop) scintillator well adapted for use with BBQ converters in calorimeters.

3.3. Position dependence study

As seen in the previous section, the main problem one has to face with a single converter is the dependence of the light output on the distance d from light source to rod. Table 2 shows that this effect varies with the scintillator used but is always large.

Further attempts to improve the homogeneity of response are made. By modifying the state of the scintillator edges, one could hope to increase the contribution of reflected light. Measurements on P₂₀, with machined edges painted with TiO₂ reflector, show surprisingly an overall light loss of $\approx 10\%$ and a dependence ($PH(d=1cm)/PH(d=9cm)$) increased from 2.1 to 2.6. Polishing the edges by diamond machining gives no important improvement on light output (5-10%) or on d dependence. In fact the map of PH for protons on the scintillator surface (Fig.7) seems to indicate that polished edges or corners, with aluminized mylar on all sides, have little influence on the position dependence, which is essentially radial. Furthermore, we tested the effect of depolishing the edge of the central hole usually just machined and found no appreciable effect. Taking out the aluminized mylar foils between scintillators caused a $\approx 5\%$ light loss and a

steeper dependence in the last 2cm near the outside edge. Comparing the rods made of plexiglas 218 (non UV absorbant, cutoff 280 nm) with equivalent rods of plexiglas 240 (UV absorbant, cutoff 380 nm), we observed an overall light loss of $\approx 20\%$, and a d dependence not significantly modified; the Cerenkov light produced in a rod by a proton or an electron is reduced by $\approx 35\%$ in the second case.

All these tests showing no easy way to reduce drastically the PH dependence on the distance to the converter rod, we tried a different configuration: a 3mm thick, 10cm wide plexiglas plate doped with 90 mg/l of BBQ and covering completely one side of the P_{14} module (see fig.1b and table 2). A similar plate, 20 cm wide, was also used on P_{20} . Fig.8 shows the response in PH of module P_{14} as a function of the distance to the plate. The PH in the same module, but equipped with a rod (P_{13}), is also represented. The light outputs are in fact of comparable size if one takes into account the differences in 'extraction' areas. The dependence on d is clearly less sharp for the plate, since $PH(d=1\text{ cm})/PH(d=4\text{ cm})$ is 1.5 for the plate and 2.0 for the rod. This can be expected since the variation in solid angle for different positions in the scintillator is smaller in the case of a plate.

3.4. Conclusions on single extraction devices

Calorimeters with fine sampling and good light yield are relatively easy and cheap to build using PMMA scintillators and BBQ converter rods or plates. With a sampling of 1mm of lead and 5mm Plexiglas plates for instance, resolutions of $\sigma/E \approx 8\%/\sqrt{E}$ should be readily achieved. On the other hand, the inhomogeneity of response of such a module will in general spoil the energy resolution, unless one is

able to reduce or overcome the position dependence.

It can be reduced by working along following lines, suggested by our studies or by other authors:

- use thick scintillator (1-2 cm) of 'long' attenuation length such as NE104b (in conflict with compactness and cost),
- use converter plates rather than rods,
- find better scintillator shapes such as triangles [8],
- add a first wave-shifter inside the scintillator such as Popop (350-->420nm) to increase the effective attenuation length [7,14],
- use an U.V. absorbant plexiglas for the converter [8,9],
- try to add a U.V. filter between scintillator and converter [12],
- use progressive reflectors between scintillators, such as absorptive paint near the converter, no reflector at intermediate distance and aluminized mylar far from converter [12],
- multiply converter rods or plates joined to a common phototube [12], in a way to average the response.

These methods either cause large light losses or make the construction uneasy; in all cases, only a partial improvement can be expected and an homogeneity at the level of a few percent seems hard to reach.

To overcome the inhomogeneity, one can determine the shower position, thus allowing correction for the dependence. Two possibilities may be used:

- determine the position by an outside detector; for photons, this means a preshower detector, which would spoil the energy resolution.
- determine the position in the calorimeter itself; for small cells ($<10 \times 10 \text{ cm}^2$) seen along one side by a converter plate, the leaks in

the adjacent cells allow to determine the shower position ($\sigma \approx 1.5$ cm [14]) and hence to correct for inhomogeneity. A more complicated method [13] using liquid scintillator with optical segmentation and BBQ converter readout along three coordinates should yield the shower location to a few mm. The simplest method seems to be the extraction of the light by two independent converter plates in order to obtain the position by comparing the amplitudes [10,9]. Since we are aiming for relatively large cells, compact and easy to construct, the latter solution seems to be the most attractive.

4. MEASUREMENTS ON DOUBLE EXTRACTION PROTOTYPES

4.1. A new scintillator

Having decided to use a two-plate light extraction mode, in which the short attenuation length of scintillators is no more a drawback, we were naturally interested by polystyrene (PS), which is used as scintillator [18] in the electromagnetic calorimeter of a CERN experiment (UA1). PS, produced massively in thin layers (≈ 1 mm) for wrapping, can be obtained in sheets from 1 to 6 mm by extrusion of the granular product. When doped with 1% polybutadiene (PBD) and .1% anti-oxidant and coupled with BBQ converters, its light yield is nearly twice that of NE110 and the measured attenuation length is of the order of 25-30 cm [9]. The extrusion procedure allows to guarantee a tolerance on the thickness of a few percent. The present price is already inferior to that of Plexipop or Altustipe and should drop if massively produced as scintillator.

In our prototypes P_{50} and P_{25} , we used 60 PS plates of 1.5 mm, thickness which was available at that time. To compare the amount of

light collected with the light from P_{20} (NE104b), the resolutions in pulse-height measured with protons at various distances from one plate can be used. At a 5cm distance, ≈ 0.7 phe/plate are collected in P_{50} , compared to ≈ 2.2 phe/plate in P_{20} . If we normalize P_{50} to a 5mm plate thickness, we obtain ≈ 2.3 phe. We can conclude that PS and NE104b scintillators yield comparable quantities of light, when coupled to BBQ.

4.2. Position dependence and resolution

The measured dependence of the response ($\ln PH$) on the distance to one plate (R) is shown in fig.9, where P_{50} is scanned horizontally (x) with protons at $y=0$ (see fig.4). An attenuation length of $\lambda \approx 24$ cm is observed with a sharper drop ($\lambda \approx 10$ cm) near the converter ($d < 5$ cm), and a slower decrease ($\lambda \approx 50$ cm) in the last 12cm, probably due to some contribution of the scintillator edge. The PH from the second plate (L) was also measured after equalizing R and L gains in the middle of P_{50} . These dependences, together with the linear sum $\Sigma = R+L$ (mixer LRS 428) are shown in fig.10. A variation with x of a factor $f \approx 6$ in a single plate and $f \approx 2$ for Σ can be observed.

To estimate a particle or shower position along x direction, the most sensitive parameter seems to be the PH ratio (R/L). Fig.11 shows the variation of $\ln(R/L)$ with x for protons and electrons of 1 and 5 GeV. This function is linear and the error in position evaluated from the widths of the PH distributions of L and R is nearly independent of x . The observed resolutions are $\sigma \approx 3$ cm for protons, $\sigma \approx 1.9$ cm for 1 GeV and $\sigma \approx 1.2$ cm for 5 GeV electrons, after correcting for beam energy spread as known from q_{12} measurements. For minimum ionizing particles, the resolution clearly suffers from the lack of light; for

electrons, our measurements are overestimated, since they are deduced from the PH distributions from each plate, instead of using the distributions of the ratio R/L event by event, which would be free of the sampling contribution. If we unfold this estimated contribution, a position resolution $\sigma \approx 1.5\text{cm}$ is obtained at 10GeV, which clearly improves at higher energies. Such resolutions are sufficient to correct the total PH (Σ) for shower position, since the additional contribution to the energy resolution is $\approx 5\%$ in the regions where the dependence of PH(Σ) on position is the steepest.

In order to guarantee the position and energy resolutions all over the module, it is essential to check that the PH dependence on x is not affected by the shape or intensity of the light source. Fig.12 shows the x dependence for protons, 10GeV and 100GeV electrons. The PH differing by a factor 60 between these extreme conditions, are arbitrarily normalized for easy comparison. In fact the observed dependences are very similar.

It is also essential that the variations of PH with y are sufficiently small. Fig.13 shows these variations, measured with protons at three values of x . Effects of less than 3% are observed, essentially near the edges.

4.3. Energy resolution

Spectra of the total pulse height ($\Sigma=L+R$) are taken with electrons hitting the center of P_{50} in the energy range .25 to 12 GeV. The peak positions and widths of the distributions are shown in fig.14. A linearity better than 2% is observed up to 10 GeV. The resolutions (σ/E) obtained in beam b_{16} are represented up to 12 GeV together with measurements in q_{12} up to 3 GeV, clearly showing the contribution of

the energy spread of beam b_{16} . Fig.15 shows the variation with x of the PH peak for R , L and Σ for 1 GeV electrons, together with the energy resolution σ/E measured in q_{12} beam. The latter is observed to be very constant all across the detector at a value: $\sigma/E = 10.5\% \sqrt{E}$.

A complete study of P_{25} , which only differs from P_{50} by the distance (25cm) between converter plates, shows that the sum (Σ) dips by 25% in the middle; so P_{25} yields 1.5 times more light than P_{50} . The energy resolution measured with electrons is again found to be very constant along x at a value $\sigma/E = 9.0\% \sqrt{E}$.

If we evaluate the number of photoelectrons (N_{phe}) for protons in the middle of the detector from the measured resolutions, N_{phe} for electrons can be deduced knowing that a 1GeV electron is equivalent to about 6 minimum ionizing particles, and hence the light contribution to the energy resolution is obtained. If the sampling contribution is estimated using the empirical relation: $\sigma/E = 15\% \sqrt{t}/\sqrt{E}$, where t is the sampling thickness in radiation lengths, the total expected energy resolution can be deduced as shown in table 3. A good agreement of the measured values with the expected energy resolutions is observed. The data suggest that a detector with 1mm lead and 3mm PS plates should give 7-8% $\sqrt{E}$ resolutions, depending on its size.

4.4. Complementary measurements

In view of designing a large assembly of such detectors, a few complementary measurements have been made:

- Pion rejection: The electronic efficiency on the total PH (Σ) was measured for pions and electrons in the centre of P_{50} at various energies. Fig.16 shows that pion contaminations of the order of 2% at 1 GeV and smaller at higher energies are obtained for an electron

efficiency of $\approx 90\%$. Measurements at 1 GeV, with P_{50} reduced from 13 RL to 9RL, show no significant decrease of the pion contamination.

- Converter attenuation length: the attenuation in the converter plate is measured to be $N/N_0 \approx (85 \pm 2)\%$ over 16cm, corresponding to an attenuation length of $\lambda \approx (0.98 \pm 0.15)m$; such a length is sufficient to make the effect of the depth at which a photon shower starts, negligible if the module is compact ($\approx 20cm$).

- The distance between PS edges and converter plate was varied from 1 to 12mm; a linear decrease of 2%/mm is observed showing that this parameter is not very critical. A measurement with the lead sheets set 2mm back with respect to the scintillator edges on the converter side shows a light increase of $\approx 2\%$.

- The effect of adding aluminized mylar on top and bottom of the stack as well as between scintillator and lead was measured to be only of the order of +3%.

- When forming an array of such detectors, a considerable economy could be made if one converter plate could 'view' two cells. This implies that the light produced in one cell does not pass to the next cell across the converter plate. This effect, that we call 'cross-talk', has been measured using module P_{25} with one of its converter plates (R) viewing also an adjacent module P'_{25} (similar to P_{25}). Module P'_{25} was then scanned along x with electrons of variable energy. It is observed that plate L sees only a small constant fraction (1.6%) of the light seen by R. The smallness of the cross-talk is expected, since the BBQ wave-shifted light, escaping from a converter plate and transmitted by the scintillator of an adjacent cell, cannot be absorbed massively by the next converter plate (see fig.3). This means that a single plate can be used between 2 cells and that

each time a shower occurs in a given cell, a small correction should be applied to the adjacent ones.

- A scan along x direction, with a 5mm wide beam counter, in the region of plate R of the P_{25} - P'_{25} assembly shows that the $PH(\Sigma)$, measured for 1 and 3.4 GeV electrons, passes through a smooth maximum and decreases when going into the next cell. Less than 10% inefficiency and a resolution increase to $\sigma \approx 12\% \sqrt{E}$ are observed in a ≈ 1 cm region. This interesting feature can be explained by the facts that small angles of the beam particles make very improbable the passage of an electron in the 1mm air gaps on both sides of the converter plate and that the PH given by an electron passing through some length of converter plate is comparable to the light of a several GeV electron shower occurring very near the plate. In the case of photon detection, a 2RL, 5mm wide, barrel of lead should minimize the efficiency losses in this region.

5. CONCLUSIONS AND POSSIBLE DESIGN OF A LARGE ARRAY

The principle of measuring the shower position along one coordinate by comparing the light outputs of two converter plates, and of correcting the energy measured by the linear sum of these outputs for its position dependence, has been shown to work satisfactorily. An optimized cell structure could be: 80 layers of 1mm lead and 3mm PS plates, resulting in a total of ≈ 15 RL, including some additional material for photon conversion. It is now possible to build an array of such detectors, with an overall energy resolution of less than $10\% \sqrt{E}$ and negligible efficiency losses.

For the EMC/NA9 experiment, the cell size should be such as to avoid having the two photons of a π^0 in the same cell and the posi-

tion accuracy required for $\gamma\gamma$ invariant mass reconstruction should be the same in both coordinates. This leads to square cells of 20×20 or 40×40 cm², depending on the angular region considered, with four converter plates and photomultipliers, as shown on Fig.17. Since the "cross-talk" was measured to be small, each converter plate can view two adjacent cells. If adjacent cells are interested by showers of the same event, most ambiguities may be solved by treating each pair of opposite plates separately. Each pair will provide one coordinate and the corrected energy measurement. The two independent energy measurements can then be compared and averaged.

The price of such arrays will be dominated by the electronic chain. The gain in cost with respect to a lead glass system will of course be strongly dependent on cell size. To cover ≈ 20 cm² with a mixture of 20×20 and 40×40 cm² cells as defined above, has been estimated in 1980 to cost ≈ 0.6 Million Swiss Francs provided most of the machining and assembling work can be done 'for free' in home laboratories. In fact, the construction of such modules is very simple. Polishing is only necessary for the converter plates and light-guides. The extruded polystyrene plates are delivered with excellent thickness tolerances and good surface state. They can be used with edges just machined and without any reflector; the air-gap width is rather uncritical. The only relative difficulty is to design a 'thin' structure for supporting the weight of the lead.

The four-plate scheme as designed above is advantageous for large cells. In fact, if thicker scintillator plates are used, cells of 1m² are possible with only four photomultipliers. If the required granularity is $\approx 10 \times 10$ cm² or smaller, a single-plate extraction mode is adequate, the position being then known from the leaks in the adja-

cent cells. The e/π discrimination can be improved by segmenting the calorimeter in 3-4 parts with independent read-out; this allows some determination of the shower direction, in turn useful for further rejection of pion charge-exchange processes and π/γ superpositions.

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Figure captions

Fig.1: Principle of the light collection by acrylic plates (1a) or rods (1b) doped with a wave-length shifter.

Fig.2: Beam b_{16} (CERN PS) and test set-up. Scintillation counters SC1, SC2, SC3 have approximately $3 \times 3 \text{ cm}^2$; SC4 and SC5 are scintillator fingers defining a square of 1 cm^2 . Turned by 90 degrees, they define a square of $0.5 \times 0.5 \text{ cm}^2$.

Fig.3: BBQ absorption and emission spectra. Superposed is the polybutadiene (PBD) emission spectrum. PBD is used as scintillation agent in acrylic scintillators and in polystyrene (PS).

Fig.4: Two-plate light extraction system. The 60 layers of lead and PS are pressed in place by two aluminium plates (6mm thick) fixed on a large aluminium base plate. On both sides a small barret stops the plates from sliding and the converter plates are pressed against the aluminium plates leaving a 1-2mm air gap between PS and converter.

Fig.5: Variation with electron energy of the peak position and FWHM (5a) and of the resolution σ/E (5b) for 3 lead thicknesses. The beam is hitting P_{20} at 5cm from the rod. PH always means pulse height in analyser channels (gain arbitrary) after pedestal subtraction.

Fig.6: PH as a function of distance d to the centre of the rod for P_{11} , P_{12} and P_{13} modules. The same rod and photomultiplier are used for the three measurements. The common point in the converter allows to check the normalization.

Fig.7: PH measured with protons in different points of the surface of P_{20} , with polished scintillator edges.

Fig.8: PH dependence on distance d to converter for protons. The plate or the rod are mounted successively on the same module.

Fig.9: Dependence of $\ln(PH)$ on the distance x to plate R for protons on P_{50} .

Fig.10: Dependence on x ($y=0$) of PH in plates R and L and of their linear sum Σ , for protons.

Fig.11: Variation of $\ln(R/L)$ with x ($y=0$) for protons and electrons. The errors are evaluated from the measured width of PH distributions in R and L.

Fig.12: Comparison of PH dependence on x for protons and electrons. PH is arbitrarily normalized for easy comparison of the curves.

Fig.13: Variation of PH with y at different values of x , for protons.

Fig.14: Peak position and FWHM of Σ distributions as a function of electron energy, in P_{50} at $x=24\text{cm}$ and $y=0$. Energy resolutions (σ/E) as measured in beam b_{16} and in q_{12} are read on the righthand scale.

Fig.15: Dependence of PH of L,R and Σ on x ($y=0$), for 1 GeV electrons. Corresponding resolutions (σ/E) on the righthand scale.

Fig.16: Electronic efficiencies for electrons and pions when varying the discriminator threshold on Σ , at 1,2 and 3GeV, on P_{50} for $x=24\text{cm}$ and $y=0$.

Fig.17: Possible design with four plates per cell ($20 \times 20 \text{ cm}^2$), seen from the rear; each plate is viewing two cells. The converter plates together with their light-guides (not represented) and phototubes could slide in or out between the scintillator stacks.

Table 1 Structure of test prototypes

Name	P20	P11	P12	P13	P14	P50	P25
Scintillator	NE104b	Altustipe	NE104b	Peterglass	Peterglass	PS	PS
Sensitive area (cm ²)	20*20	10*10	10*10	10*10	10*10	20*50	20*25
Thickness/layer (mm)	5	4	3	3	3	1.5	1.5
Lead thick./layer (mm)	2	2	2	2	2	1.2	1.2
Number of layers	37	43	52	52	52	60	60
Total material (rad. lengths)	14	16	19	19	19	13	13
Total thickness (cm)	27.0	27.0	27.6	27.6	27.6	17.0	17.0
Light extractor	1 rod or 1 plate	1 rod	1 rod	1 rod	1 plate	2 plates	2 plates

Table 2 Scintillator comparison

	NE 104b	Altustipe	Peterglas
Thickness/laver mm	3	4	3
Light/ NE 104b	1	0.43	0.48
Light corrected for thickness	1	0.39	0.48
d (cm) dependence PH(d=1)/PH(d=4)	1.6	1.7	2.0

Table 3 Contributions to energy resolution

		σ/E (%)					
Nphe							
		protons	1 GeV electrons	light	sampling	expected	measured
p50	30		180	7.5	6.7	10.1	10.5
p25	45		270	6.1	6.7	9.1	9.0

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig.7

Fig.8

Fig.9

Fig.10

Fig.11

Fig.12

Fig.13

Fig.14

Fig.15

Fig.16

- Scintillator
- BBQ converter plate
- Photomultiplier + shielding

Fig.17