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Overview of an Electromagnetic Calorimeter for a Linear Collider based on the Shashlik technique with longitudinal segmentation.

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Abstract

Several solutions to realize an Electromagnetic Calorimeter based on the Shashlik technique with longitudinal segmentation are considered. The possibility to build a barrel calorimeter at a Linear Collider experiment using the proposed techniques is exploited.

1 Introduction

Shashlik calorimeters are sampling calorimeters in which scintillation light is read-out via wavelength shifting (WLS) fibers running perpendicularly to the converter/absorber plates [1, 2]. This technique offers several advantages and it has to be considered as a well established safe and relatively cheap technique.

Here the Shashlik calorimeters are considered in order to realize a barrel Electromagnetic calorimeter at future linear e^+e^- colliders [3]. The present Shashlik technology can satisfy the requirements described in [4] including that of a very high granularity. A transversal segmentation of the order of 3×3 cm^2 can be easily achieved and, concerning the longitudinal segmentation, a lot of development work has been made in the last few years. Two new solutions, based on the results of a research and development project, and a third one based on the experience of the DELPHI STIC calorimeter, are proposed:

1. vacuum photodiodes inserted between adjacent towers in the front part of the calorimeter [5] (Shashlik1);
2. two types of scintillator with different decay times inserted, respectively, in the first and in the second longitudinal part of the calorimeter [6, 7, 8] (Shashlik2);
3. Silicon pad layers inserted at different depth in the calorimeter structure (Shashlik3).

In the following sections, after a review of the R&D results, the mechanical layout, the cost evaluation and the expected performance for a barrel Electromagnetic calorimeter (from now on ECAL) at a Linear Collider experiment are given for all the proposed solutions.

2 Shashlik1

In this section, a Shashlik calorimeter with the longitudinal segmentation based on vacuum photodiodes inserted between adjacent towers in the front part of the calorimeter is described.

2.1 Prototype results

A prototype detector was exposed to a beam with the aim of measuring the sampling capability and demonstrating that the insertion of diodes neither deteriorates critically the energy response nor produces significant cracks in the tower structure. The prototype had 25 Pb/scintillator towers, assembled in a 5 × 5 matrix. Each tower consisted of 140 layers of 1 mm thick lead and 1 mm thick scintillator tiles, resulting in a total depth of $25X_0$. The transversal dimension of each tower was 5 × 5 cm^2. Plastic scintillator consisting of polystyrene doped with 1.5% paraterphenyl and 0.05% POPOP was used. Optical insulation between the towers was provided by white Tyvek paper.

The blue light produced in the scintillator was carried to the photodetector at the back of the calorimeter by means of plastic optical fibers doped with green WLS. The 1 mm diameter fibers crossed the tiles in holes drilled in the lead and scintillator plates and they were uniformly distributed with a density of 1 fiber/cm^2. All the fibers from the same tower were bundled together at the back and connected to photodetectors (1“ Hamamatsu R2149-03 phototetrodes). In the first $8X_0$ the tiles had a smaller transverse dimension to provide room for the housing of the diodes ($9 \times 5 \times 0.5$ cm^3 EMI vacuum photodiode prototype D437 and $5 \times 5 \times 0.5$ cm^3 Hamamatsu vacuum photodiode prototype SPTXC0046).

A very good e/π separation - $\epsilon_\pi = (4 \pm 1.5) \times 10^{-4}$ with $\epsilon_e = 0.9$ at 50 GeV - was achieved and the following energy resolution

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{9.6\%}{\sqrt{E}} + 0.5\%\right)^2 + \left(\frac{0.130}{E}\right)^2} \tag{1}$$

was obtained, where E is expressed in GeV.

The position resolution of the prototype at the tower center was 1.6 mm with 50 GeV electrons.

A detailed discussion of the results can be found in [5].

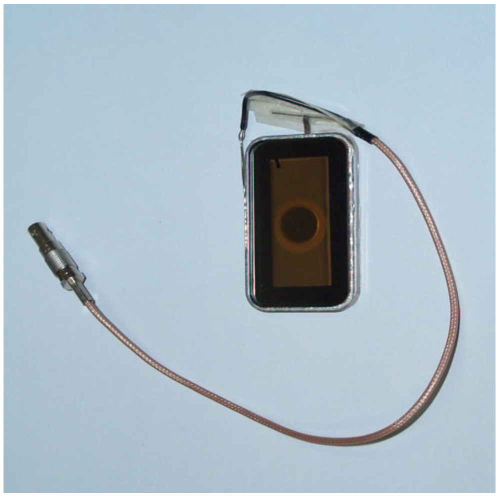

Figure 1: *The* $5 \times 3 \times 0.5$ *cm*^{3} *Hamamatsu PPTXC00052 photodiode.*

In order to study the feasibility of a calorimeter with higher granularity (3×3 cm^2 lateral size), a smaller vacuum photodiode ($5 \times 3 \times 0.5$ cm^3 Hamamatsu prototype PPTXC00052 shown in fig. 1.) was tested. The energy response to the early shower development of 30 and 50 GeV electrons and 30 GeV pions is shown in fig. 2.

2.2 Mechanical layout for a barrel ECAL

The smallest unit of the calorimeter is the tower made of 140 layers of 1 mm thick lead and 1 mm thick scintillator tiles, for a total depth of $25X_0$. The lateral dimensions of the tower goes from $\sim 3.2 \times 3.3$ cm^2 in the front face to $\sim 3.8 \times 3.9$ cm^2 in the back face. In the first 5 cm the tiles have a smaller transverse dimension to provide room for the housing of the vacuum photodiodes which are in direct optical contact with the lateral side of the scintillator tiles. For each tower the blue light produced by the scintillator is carried to the back of the calorimeter by means of 9 plastic optical fibers doped with green WLS connected to a photodetector. The light transmission between the plastic scintillator and the fibers is in air. Light collection is increased by aluminizing the fiber

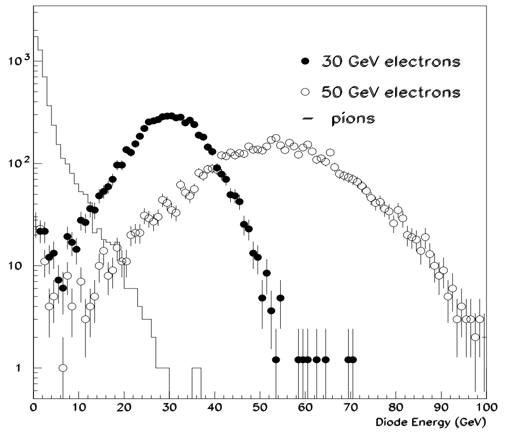

Figure 2: *Energy response for 30 and 50 GeV electrons and for 30 GeV pions for the* $5 \times 3 \times 0.5$ cm^3 *Hamamatsu photodiode.*

end not viewed by the photodetector by sputtering. Two types of photodetector can be considered: vacuum phototetrodes and APD's. The vacuum photodiode signals are taken to the tower end by means of thin cables.

A mechanical unit called a module contains 18 (3×6) towers. The calorimeter mechanical structure consists of rows of 21 modules (Fig. 3) located in order to ensure a quasi-pointing geometry along the z coordinate. Each row covers 112.1 mrad in the azimuth angle ϕ and then the whole calorimeter is made by 56×2 such rows for the two z directions. A central ring of 56 modules covers the region at $z = 0$ in order to avoid dead zones pointing to the interaction region. The total number of modules is therefore 2408 corresponding to 43344 towers. The global detector layout is shown in Fig. 4.

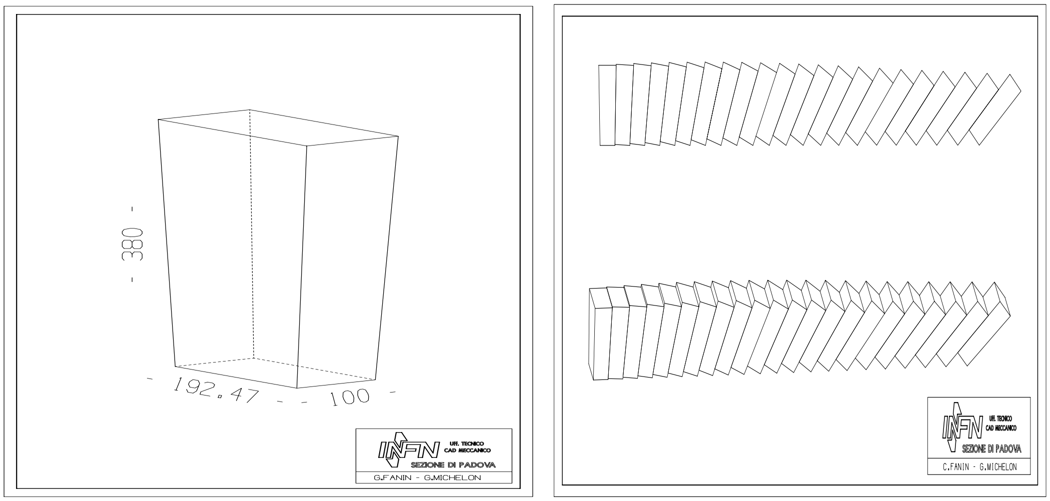

Figure 3: Geometrical layout of a Module and a row of 21 +1 Modules

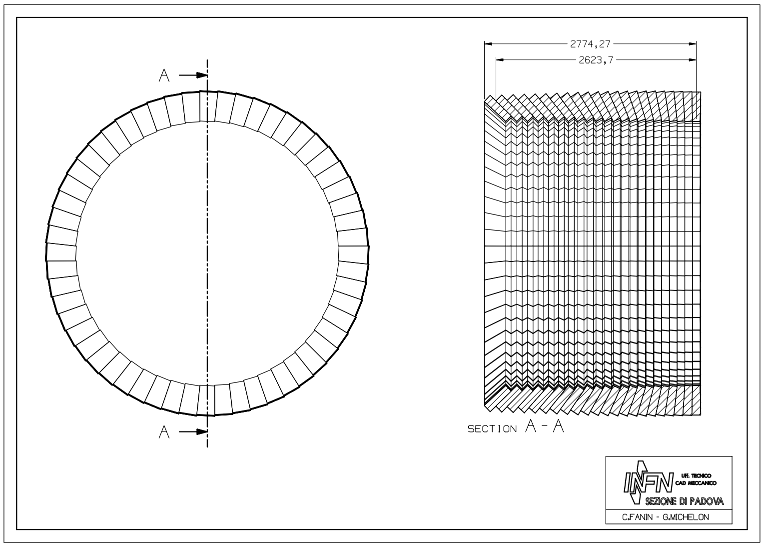

Figure 4: Global geometrical layout of the proposed barrel ECAL

2.3 Cost evaluation

This solution consists of 43344 towers with double read-out corresponding to 86688 electronic channels. The cost evaluation (Table 1) is based on the presently available prices. A total cost of about 20 M euro's is expected for the barrel ECAL. By scaling the geometrical coverage, the endcaps are estimated to cost 6.6 M euro's.

Item	unitary cost (eur)	Total cost (Meur)
Module production	3089	7.4
Fibers	170(Module)	0.4
Photodetectors (APD)	33	1.4
Photodetectors (Vacuum Photodiodes)	140	6.1
R.O. Electronics	50	4.4
Total		19.7

Table 1: Cost estimate for a shashlik-based barrel ECAL with vacuum photodiode. By scaling the geometrical coverage, the endcaps are estimated to cost 6.6 M euro's.

3 Shashlik2

In this section, a Shashlik calorimeter is described with the longitudinal segmentation based on two types of scintillator with different decay times inserted in the first and in the second longitudinal part of the calorimeter.

3.1 Prototype results

The prototype exposed to a beam had 9 Pb/scintillator towers ($5 \times 5 \times 28$ cm^3) assembled in a 3×3 matrix. In each tower, the scintillator Bicron BC-444, characterized by a decay time of about 250 ns, was used in the first 29 layers (corresponding to the first 5 X_0). Its decay time is much longer than the decay time of the standard scintillator which is faster than 10 ns, and which was used in the residual 100 layers. The light produced in each tower by both the fast and the slow scintillator was carried to the same photodetector by means of KY11 fibers from Kuraray. These are fast enough not to deteriorate the separation between the fast and the slow scintillator signals. Various photomultipliers were tested in order to optimize the separation between the fast and the slow scintillator signals. Fig. 5 shows the time response to the fast scintillator signal of the photomultipliers FEU 84-3 and FEU 115-M used respectively in a 1999 run at the CERN West Area and in a 2000 run at the CERN North Area.

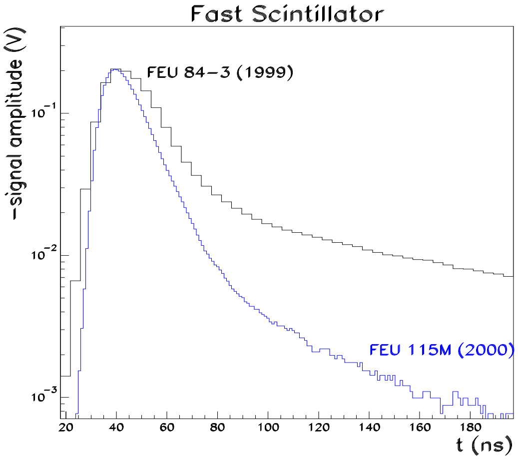

Figure 5: Time profile of the signals from FEU 84-3 and FEU 115-M photomultipliers for a fast scintillator.

The read-out was performed by splitting the signal by means of a passive splitter and by sampling with two differently gated ADC's. The first gate (referred to in the following as the narrow gate) was 50 ns wide. It started at the signal front rise in order to convert mainly the fast component. The second gate (referred to in the following as the wide gate) had a 50 ns delay with respect to the narrow gate and it was 150 ns wide in order to convert a large fraction of the long decay time component (see fig. 6).

The two scintillators had different light yields and, after a cross calibration of the two components, the resolution improves, as it is shown in fig. 7. From a preliminary analysis of the data collected in the 2000 runs the energy resolution can be parametrized (see fig. 8) as a function of the beam energy by:

$$\frac{\sigma(E)}{E} = \frac{14.2\%}{\sqrt{E}} + 0.6\% \qquad (2)$$

where E is expressed in GeV. The signal extracted from the slow component versus the

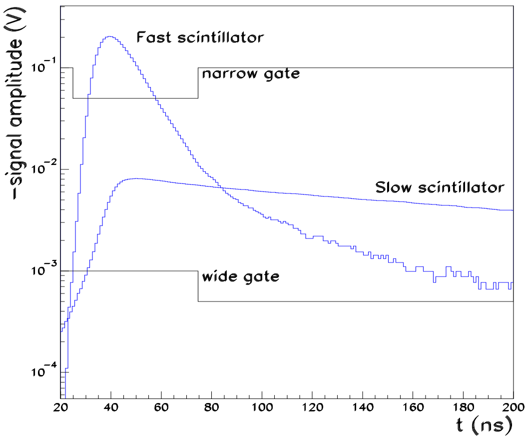

Figure 6: *Time profile of the signals from fast and slow scintillator for FEU 115-M photomultiplier. The narrow and wide gates are also indicated.*

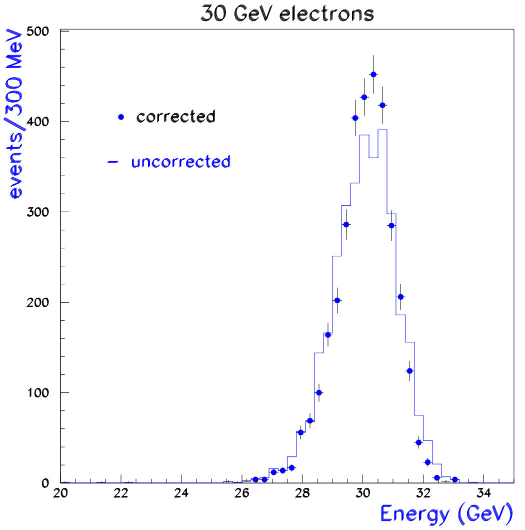

Figure 7: *Energy resolution, for 30 GeV electrons, before and after calibration between the slow and the fast scintillator.*

total energy is shown in fig. 9 for 30 GeV electrons and pions. The discriminating power of the E_{slow} information (fig. 10) improves the separation capability by a factor ~ 2 w.r.t. the E/p ratio. These results agree with the results from the 1999 data taking [6] and prove the technical feasibility of the proposed method.

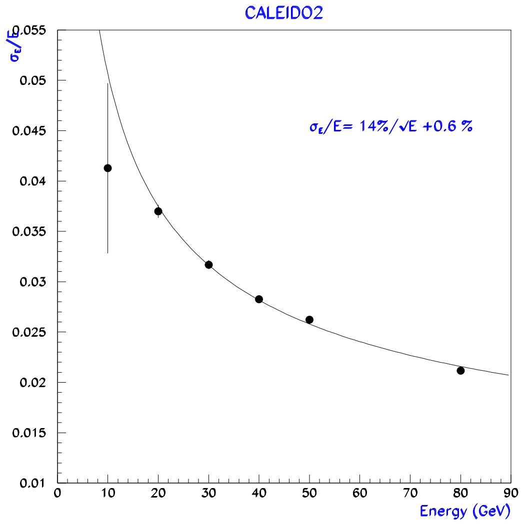

Figure 8: *Energy resolution as function of the electron energy.*

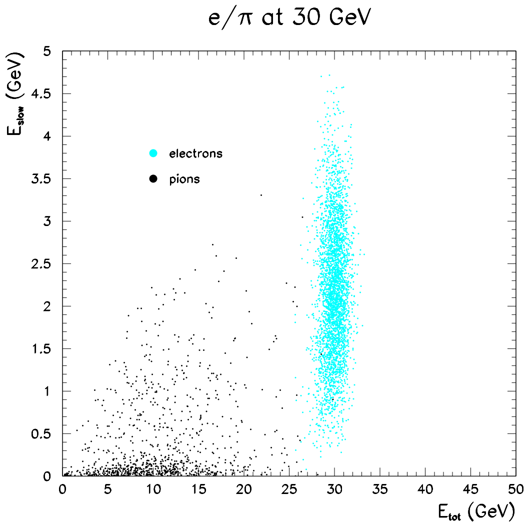

Figure 9: *Energy in the slow scintillator versus total energy for electrons and pions at 30 GeV.*

3.2 Mechanical layout for a barrel ElectroMagnetic Calorimeter

A lateral granularity of $\sim 3 \times 3$ cm^2 can be obtained in a simple way by using large (i.e. $\sim 20 \times 10$ cm^2) absorber and scintillator plates and confining the scintillation light inside the defined granularity region. The light confinement can be achieved by means of groves in the scintillator plates (fig.11).

The smallest lateral unit of the calorimeter is the cell corresponding to the tower of

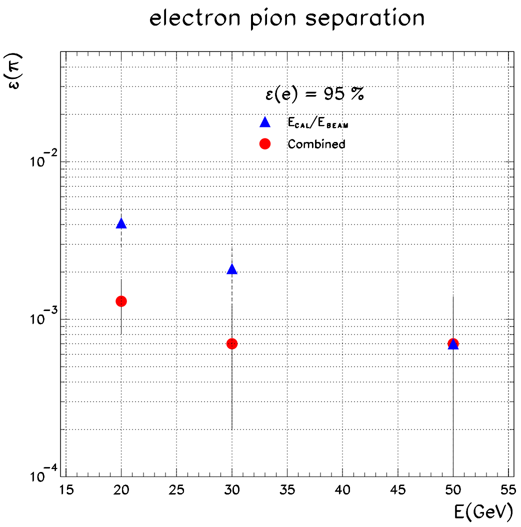

Figure 10: *Pion contamination versus energy for 95% electron efficiency.*

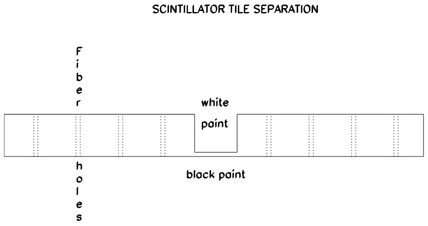

Figure 11: Layout of the scintillator plate profile with an example of grove for light confinement.

Shashlik1. Each cell consists of 140 layers of 1 mm thick lead and 1 mm thick scintillator plates, resulting in a total depth of $25X_0$. In the first $5X_0$ the scintillator plates consist of long decay time scintillator while the remaining plates are based on standard plastic scintillator (faster than 10 ns). For each cell the blue light produced by both scintillators is carried to the back of the calorimeter by means of 9 plastic optical fibers doped with green WLS. At the end of the detector the WLS optical fibers are connected to clear long attenuation-length fibers in order to bring the light signal outside of the high magnetic field region where it can be read by photomultipliers (PM).

A mechanical unit called module contains 18 (3×6) lateral cells built by means of scintillator layers shaped as in fig. 11. All the cells in a module are read independently by bundling their 9 fibers and connecting them to the same PM. The module external layout, the mechanical row-based structure and the global detector layout are the same as the ones described in the previous section and shown in fig. 3 and 4. Therefore the total number of modules is the same as the previous one and the corresponding number of cells is 43344.

3.3 Cost evaluation

This solution consists of 2408 Modules for a total of 43344 cells corresponding to the same number of electronic channels. The cost evaluation (Table 2) is based on the presently available prices. A total cost of about 15 M euro's is expected for the barrel electromagnetic calorimeters.

Item	unitary cost (eur)	Total cost (Meur)
Module production	3089	7.4
Fibers	170(Module)	0.4
Photodetectors	100	4.3
R.O. Electronics	50	2.2
Total		14.3

Table 2: Cost estimate for a shashlik-based barrel ECAL with two decay-time scintillators. By scaling the geometrical coverage, the endcaps are estimated to cost less than 5 M euro's.

Concerning the endcaps, an electromagnetic calorimeter built with the same technique is estimated to cost less than 5 M euro's by scaling the geometrical coverage w.r.t. the barrel one.

4 Shashlik3

In order to increase the granularity of the electromagnetic calorimeter, the Shashlik2 prototype could be modified, by inserting 3 layers of silicon sensors.

The advantage of the higher granularity consists not only in a better electron-pion separation, but also in a more accurate association of the energy depositions to the tracks, which is a key goal in the high density jet environment of the linear collider. The silicon layers are proposed to be placed at a depth of 2, 6 and 12 X_0. The granularity of the silicon sensors is $\sim 1 \times 1$ cm^2.

The only modification with respect to the standard techniques for silicon active layers inside calorimeters consists in the holes which have to be drilled in order to make thw WLS fibers to go through. This problem has already been succesfully solved in the DELPHI STIC luminometer [10], where the smaller pitch of the silicon strips put much more severe precision requirements compared to this proposal.

The cost evaluation (Table 3) is based on the presently available prices. Taking into account the silicon area covering each module (3×10 cm $\times$ 19.2 cm) and a unit price of 3 \$/cm^2 for the silicon wafers, the total cost for the silicon pads in the barrel part (2408 modules) is about 4.5 M Euros and therefore this solution is not much more expensive

Item	unitary cost (eur)	Total cost (Meur)
Module production	3089	7.4
Fibers	170(Module)	0.4
Photodetectors	100	4.3
R.O. Electronics	50	2.2
Silicon planes	104	4.5
Si Front-end Electronics	20	0.8
Total		19.6

Table 3: Cost estimate for a shashlik-based barrel ECAL with three planes of Si pads. By scaling the cost according to the surface, the endcaps are estimated to cost about 6.5 M euros.

than the previous one. The total cost for a barrel ECAL with this solution is about 20 M euro's.

By scaling the cost according to the surface, the endcaps are estimated to cost about 6.5 M euros.

5 Conclusions

Beam tests have demonstrated the technical feasibility of longitudinally segmented shashlik calorimeters in which longitudinal sampling is performed by lateral vacuum photodiodes or by using two scintillator types with different decay times. Performance in terms of energy resolution, impact point reconstruction and e/π separation are adequate for applications at future e^+e^- collider experiments. Three solutions for a barrel Electro-Magnetic calorimeter for a future Linear Collider experiment are presented, two based on the above-mentioned techniques, the third one using planes of silicon pads.

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