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The RD52/DREAM collaboration

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ABSTRACT: A small detector (6 radiation lenghts in total) divided into two sections of four times lead-quartz-scintillator tiles, each with a separate readout for Čerenkov and scintillation light has been tested. The results for high energy muons and electrons are presented. The measured Čerenkov light yield for electrons is about 50 Č.p.e. per deposited GeV.

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Contents

1 Introduction

In non-compensating calorimeters the dominant contribution to the energy resolution comes from the fluctuation of the electromagnetic component in the shower. The dual readout method aims at measuring the correct energy of a shower by a dual readout of the signal. In the first calorimeter of this type, the DREAM calorimeter [1], the two active media were scintillating fibers to measure the dE/dx of every charged particle and clear (quartz or plastic) fibers to measure the Čerenkov light from relativistic particles (mostly electrons and positrons). By combining the two signals, the fraction of the electromagnetic energy was measured event-by-event and this allowed the determination of the total shower energy with an improved resolution. A limitation in the resolution of the DREAM calorimeter originated from the small number of the collected Čerenkov photoelectrons (8–18 Č.p.e. per deposited GeV).

The dual readout method has been extended by the DREAM Collaboration also to electromagnetic calorimeters to be placed in front of hadronic calorimeters. Several tests performed with homogeneous crystals (PbWO, BGO) [2] proved the possibility of reading out in the same crystal both signals (scintillation and Čerenkov emission). The measured Čerenkov light yield was larger than 30 Č.p.e. per GeV in BGO [3] and about 60 Č.p.e. per GeV in PbWO crystals doped with molybdenum [4]. Matrices of crystals used as electromagnetic calorimeters were also studied [5]. Recently a new larger and improved fiber calorimeter [6, 7] for full hadronic shower containment has been tested.

In the present paper we present the results of the tests performed to extend the dual readout method to a sampling calorimeter composed of tiles of absorber interleaved with tiles of quartz and of scintillator.

2 Experimental setup

The measurements on a small prototype of a sampling calorimeter were performed in July and October 2010 at the H8 beam line of the Super Proton Synchrotron at CERN. The detector, named
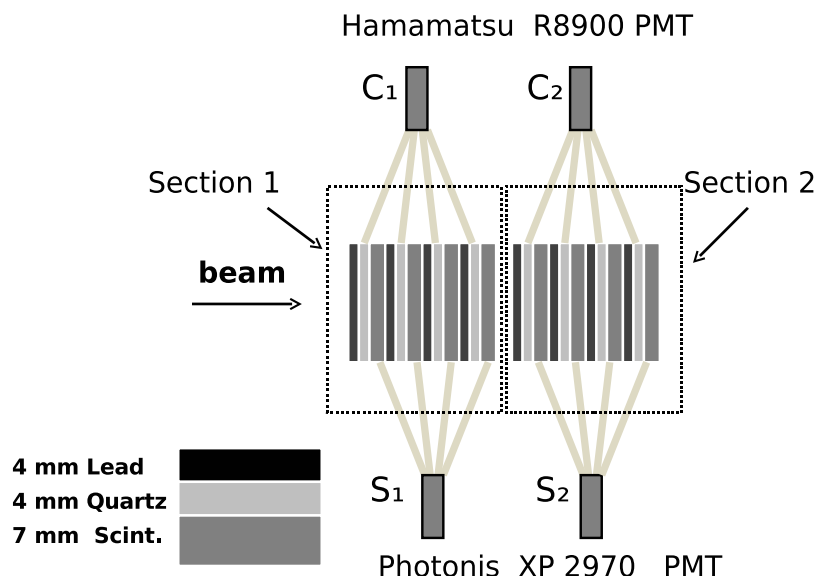
Figure 1. The QSTile prototype composed by two sections with separate readout for Čerenkov and scintillation light.

QSTile, is composed of two readout sections. Each section is made of four wafers of lead, quartz and plastic scintillator tiles as shown in figure 1. All tiles have an area of $9 \times 9\,\mathrm{cm}^2$; the thicknesses are 0.4 cm for the lead and quartz tiles, and 0.7 cm for the scintillating tiles. Each tile is wrapped in thin aluminum foils. The detector is about 6 radiation lengths as total depth and the Molière radius is 3.7 cm. For each section the light from the four quartz tiles is collected on one side of the detector through four light guides, grouped together and fed to two Hamamatsu R8900 photomultiplier tubes ($C1$ and $C2$) operated at 900 V. The signals in the scintillator tiles are collected for each section on another side of the detector through similar light guides and readout by Photonis XP2970 tubes ($S1$ and $S2$) operated at 1100 V.

The QSTile detector was placed on a platform that could rotate around a vertical axis passing through the geometrical center of the detector as shown in figure 2. The angle θ mentioned in the following is the angle between the detector longitudinal axis and the beam line. The measurements were taken at $\theta = 0°$, that is with particles impinging perpendicular to the front face of the detector, and at $\theta = 12°$, a tilted detector position, that weakly improves the collection of Čerenkov photons radiated on a cone of $46°$ aperture with respect to the direction of the beam particles.

Along the beam line the QSTile detector was followed by the original DREAM fiber calorimeter [1] used in the present tests only to identify the type of the particles in the beam. The trigger to the data acquisition system was provided by the coincidence between the logic signals from two small scintillator counters (TC), 2.5 mm thick and with an area of overlap equal to $4 \times 4\,\mathrm{cm}^2$.

A single VME crate hosted all the needed readout and control boards. The signals from the DREAM calorimeter were integrated and digitized with a sensitivity of 100 fC/count on 12-bit QDC V792 CAEN modules. The signals from the QSTile detector were recorded by means of a Tektronics TDS 7254B digital oscilloscope,[1] which provided a sampling capability of 5 GS/s, at an

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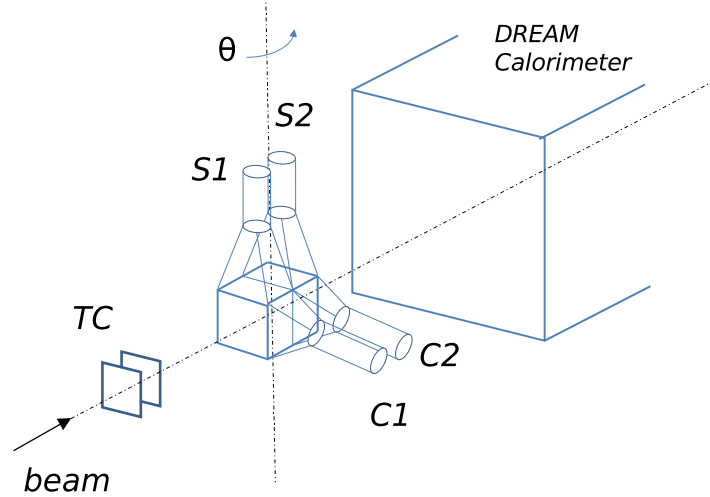[1]http://www.tek.com/site/ps/0,,55-13766-SPECS_EN,00.html.

Figure 2. Experimental setup for the beam test of the QSTile prototype.

analog bandwidth of 2.5 GHz over four input channels. For the tests described in this paper the four channels were used to sample the signals of the four PMTs of the QSTile module. Each channel had 532 samples of 0.8 ns for a total time interval of 425.6 ns. The oscilloscope gain (scale) was tuned such as to optimize the exploitation of the 8-bit dynamic range, i.e. by choosing the sensitivity such that the overflow rate was almost negligible.

The SPS provided beam particles during a spill of 9.6 s with a repetition period of 48 s. During the spill all events were subsequently recorded in the internal memory of the oscilloscope with a maximum acquisition rate of ~ 500 Hz limited by the size of the internal buffer.

3 Analysis of the muon signals

About 23% of the particles in the 180 GeV electron beam in July 2010 were muons. They are selected in this analysis with a cut on the signal in the DREAM calorimeter. The average amplitudes of the signals from the photomultipliers $C1/C2$ are about 8/7 mV and 10/9 mV for particles impinging on the detector at $\theta = 0°$ and $\theta = 12°$. The distributions of the charge collected with a 32 ns (48 ns) gate for the Čerenkov (scintillator) signals are reported in figure 3 for $\theta = 12°$. Similar distributions are observed at $\theta = 0°$.

The large fraction of events with no signal in the distributions for $C1$ and $C2$ suggests a small average number for the collected photoelectrons. To fit the data we assume that the distribution of the measured charge q is described by a Poisson function for the photoelectron statistics convoluted with a Gaussian function to account for the smearing due to the electronic noise:

$$f(q) = A \cdot \sum_{k=0}^{k=N} \frac{m^k e^{-m}}{k!} \cdot \frac{1}{\sqrt{2\pi}\sigma_q} \cdot e^{-\frac{(q - q_e \cdot k - q_o)^2}{2(\sigma_q)^2}} \tag{3.1}$$

where k is the number of photoelectrons, m its average, A an overall normalization factor, q_e the average collected charge for one photoelectron, q_o an offset in the charge distribution that results
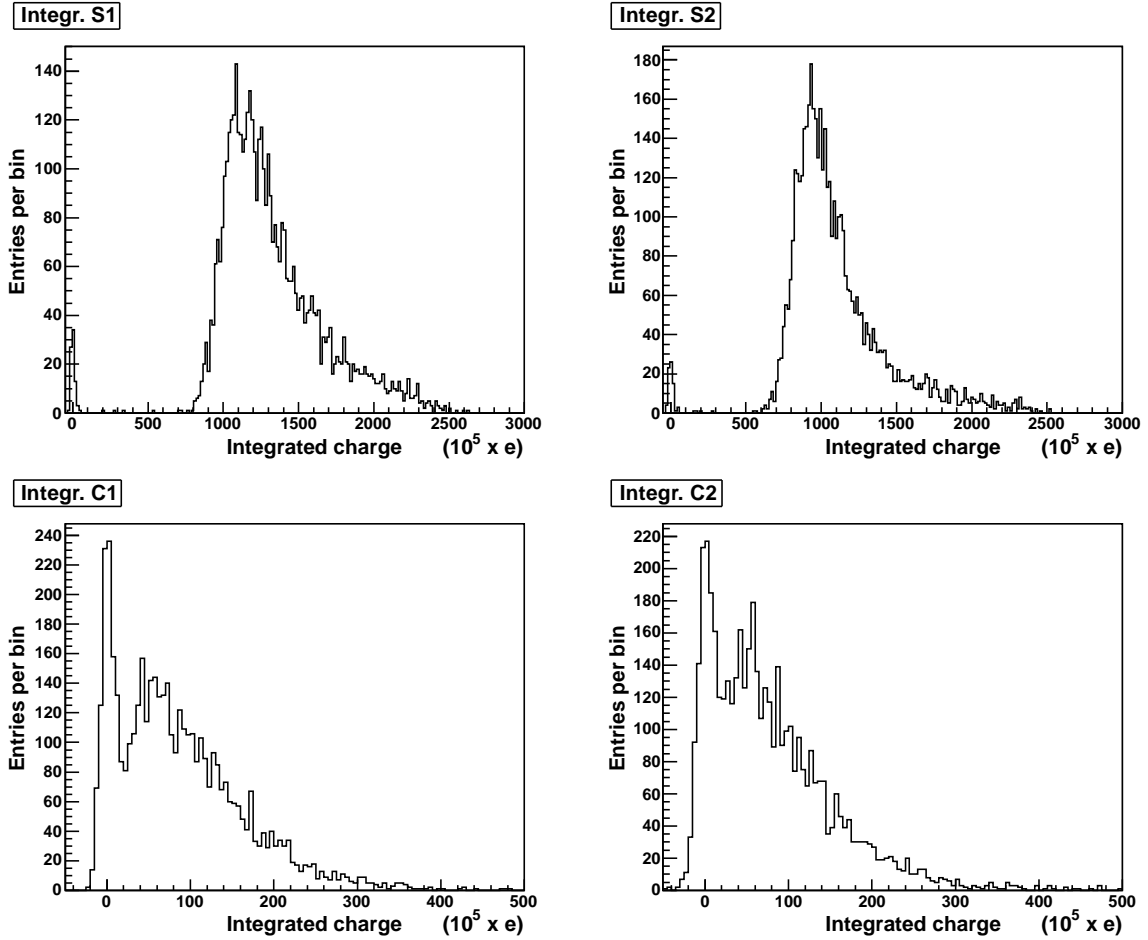
Figure 3. Charge distributions for scintillation phototubes $S1$ and $S2$ (top) and for Čerenkov phototubes $C1$ and $C2$ (bottom) in runs with muons impinging on the QSTile tilted at $\theta = 12°$. Charge is given in units equal to 10^5 electrons.

to be negligible from the fit and σ_q the rms of the noise for the total charge collected at the anode of the photomultiplier.

In a photomultiplier the noise σ_q consists of two contributions: a shot noise term σ_S proportional to the square root of the signal current, that is generated from fluctuations on the secondary electron emission in the PMT amplification, and a noise term σ_e independent from the light signal, which accounts for the fluctuations in the dark current, for background light signals, for the white electronic noise and for the limited resolution in the readout (only 8 bits). Then in our fit we assume:

$$\sigma_q^2 = \sigma_S^2 + \sigma_e^2 = a \cdot k + \sigma_e^2 \tag{3.2}$$

where a and σ_e are two parameters to be determined.

The results of the fit to the charge distributions in Čerenkov $C1$ PMT for two runs with muons impinging on the $12°$ tilted and the untilted prototype are presented in figure 4. The contributions from events with 0, 1, 2, 3 and 4 photoelectrons are shown. To remove from the fits fake triggers and double tracks only events with signals $500 < S1 < 1300$ and $500 < S2 < 1270$ (see figure 3)
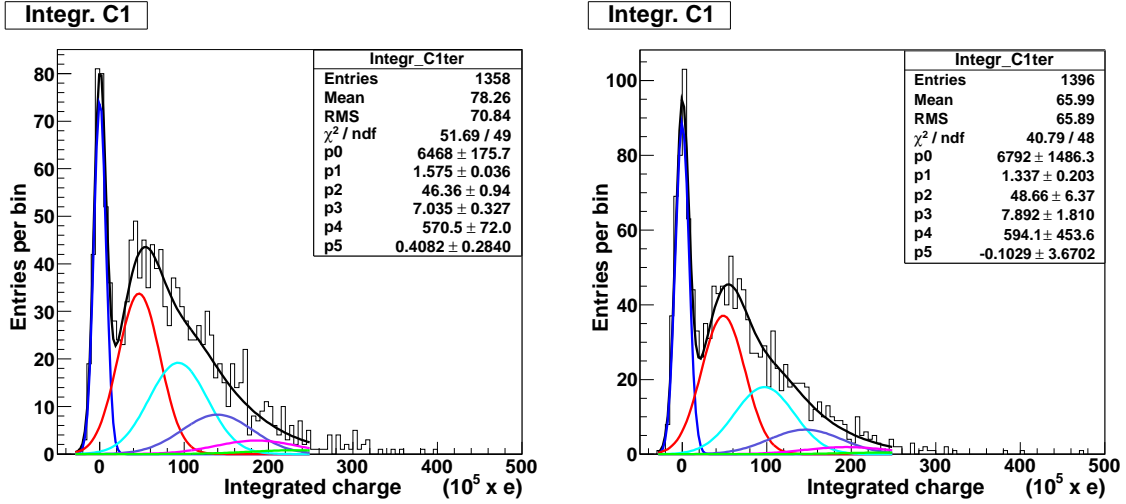
Figure 4. Fit to the charge distributions for Čerenkov $C1$ PMT in two runs with muons impinging on the 12° tilted (at left) and the untilted (at right) prototype. The contributions from events with 0, 1, 2, 3 and 4 photoelectrons are shown. Charge is measured in units of 10^5 electrons.

Table 1. Average number of photoelectrons collected in the two sections for 180 GeV muons.

	12° tilted	untilted
PMT Čerenkov C1	1.63 ± 0.02	1.30 ± 0.01
PMT Čerenkov C2	1.68 ± 0.01	1.38 ± 0.02

have been considered. The average number of the Čerenkov photoelectrons in the two sections of the QSTile fluctuates from one run to the other by a few per cent. The weighted averages for the two sections and for the two positions of the prototype are reported in table 1.

The value of the parameter q_e in the fits (p2 in figure 4) gives the average charge collected for one photoelectron and it is also a measure of the gain of the two PMTs of the Čerenkov counters at 900 V: $4.4 \cdot 10^6$ ($4.6 \cdot 10^6$) for $C1$ and $3.9 \cdot 10^6$ ($3.9 \cdot 10^6$) for $C2$ in the tilted (untilted) detector.

4   Analysis of the electron signals

Data from a 80 GeV electron beam were collected in October 2010. Figures 5 and 6 show the charge spectra of the four signals for the untilted and for the 12° tilted QSTile respectively. The small signals are produced by muons and non-showering pions while the large signals by 80 GeV showering electrons. To select the electrons, the correlation between the Čerenkov signals $C1$ and $C2$ in the two sections has been considered (see for instance figure 7 for the tilted detector). Electrons differ from muons and pions by a much larger signal in the second section due to secondary particle multiplication in the shower and then they can be separated by a line as shown in figure 7.

A saturation due to a too high voltage in PMTs is present in the distributions for $S2$ at top right of figures 5 and 6 then in the following of this paper the analysis will consider only the signals from the Čerenkov counters.
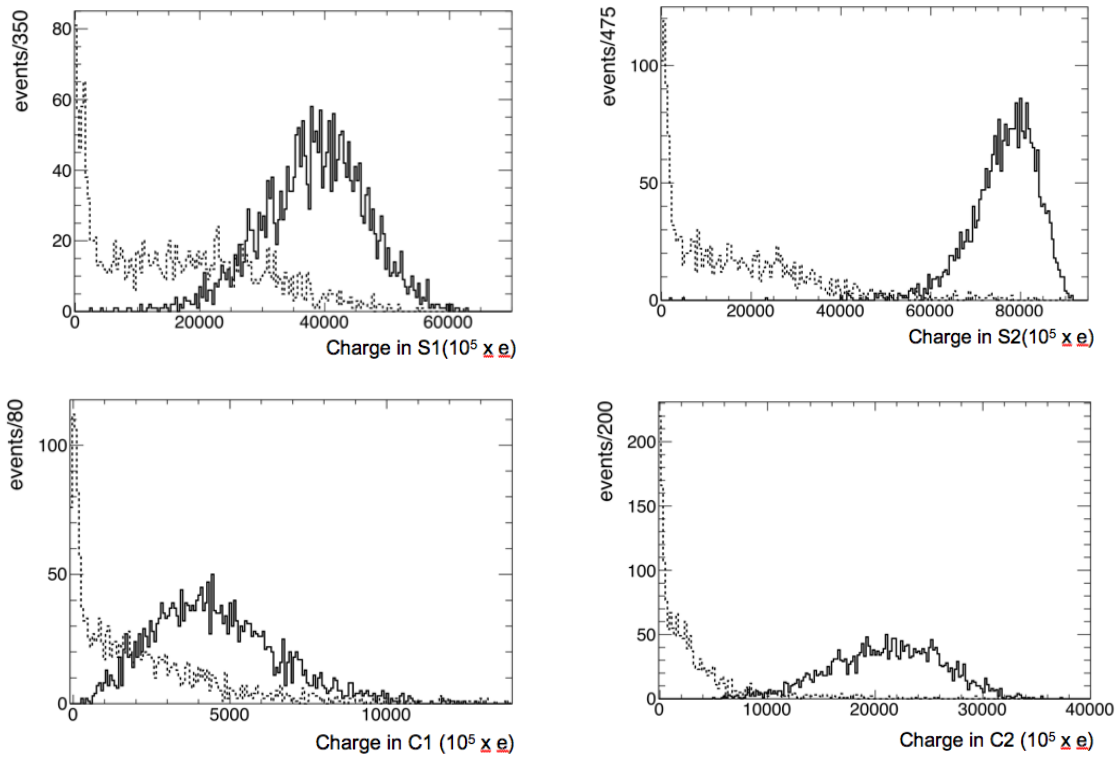
Figure 5. Charge spectra in the untilted QSTile exposed to 80 GeV electron beam. Scintillation (top) and Čerenkov (bottom) charge spectra in the first (left) and second (right) section. The two separated distributions for electrons (full line) and for the other particles (dotted line) are shown.

Table 2. Average (most probable) number of Čerenkov photoelectrons collected in the two sections for 80 GeV electrons for the 12° tilted and untilted detector.

	12° tilted	untilted
Section 1	109 (103)	101 (93)
Section 2	612 (676)	540 (542)

To measure the Čerenkov light yield in the electron signals we can refer either to the average or to the estimated maximum of the distributions in figures 5 and 6. Using the average signals for one photoelectron measured in the previous muon data analysis, these values can be expressed in terms of a number of photoelectrons and are reported in table 2.

A GEANT4 simulation[2] of 80 GeV electrons in the QSTile detector predicts for the 12° tilted/untilted positions the deposited energies equal to 1.55/1.42 GeV for the first section and 12.15/11.35 GeV for the second section. From these values we get the Č.p.e. yield per GeV reported in table 3. The Č.p.e. yield per GeV is larger in the first section than in the second one (about 70 vs 50). This difference is justified considering the two fractions given by the energy
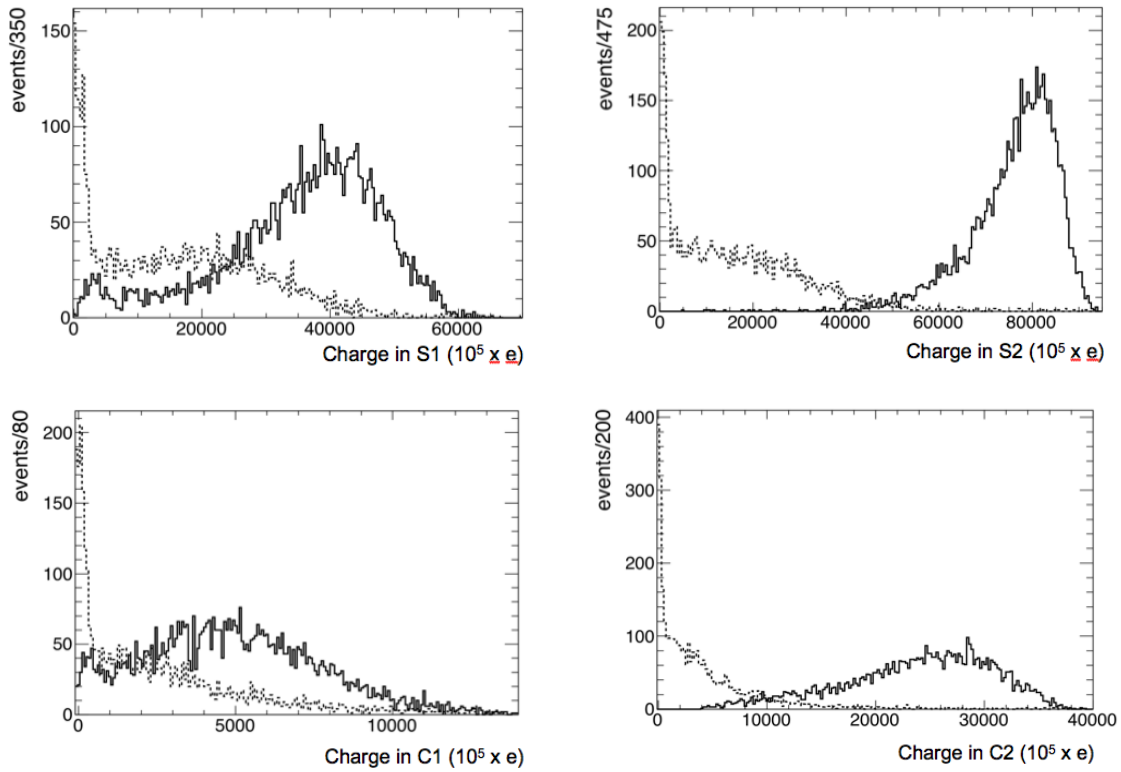
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[2]GEANT4 9.1(.p02) [8].

Figure 6. Charge spectra in the 12° tilted QSTile exposed to 80 GeV electron beam. Scintillation (top) and Čerenkov (bottom) charge spectra in the first (left) and second (right) section. The two separated distributions for electrons (full line) and for the other particles (dotted line) are shown.

Table 3. Average (most probable) number of Čerenkov photoelectrons per deposited GeV in the two sections for 80 GeV electrons for the 12° tilted and untilted detector.

	12° tilted	untilted
Section 1	70 (67)	71 (66)
Section 2	50 (56)	48 (48)

deposited only in the quartz tiles of a section over the total energy deposited in that section. From the GEANT4 simulation these fractions are 0.18 and 0.14 for the first and the second section respectively both for normal impinging and 12° tilted beams. The ratio of these two fractions is 1.29 comparable to the ratio 1.40 of the Č.p.e. yields per GeV measured in the two sections.

5 Conclusions

The dual readout in calorimetry was already tested in sampling fiber calorimeters and in homogeneous calorimeters (several different crystals). In this paper we have presented for the first time the results from a test of a small detector where the dual readout of the signal is done by scintillator and quartz tiles. In dual readout calorimeters a critical parameter for the resolution is the
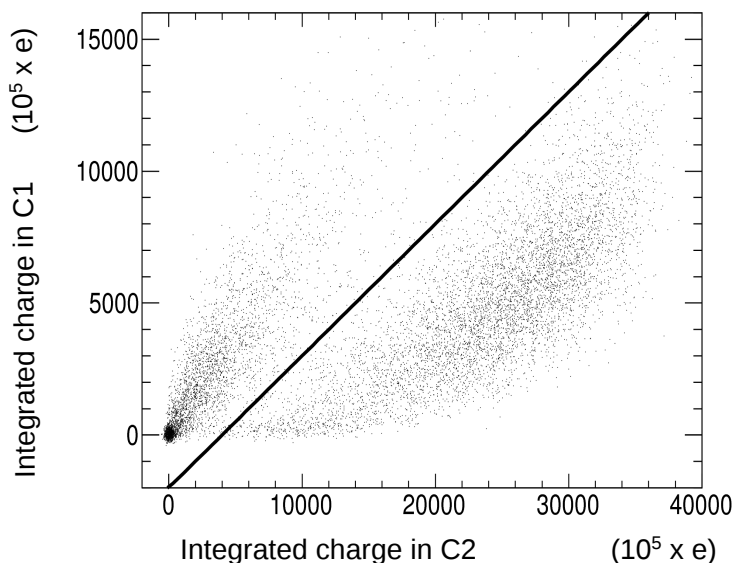
Figure 7. Correlation between the Čerenkov signals *C*1 and *C*2 in the two sections of the tilted detector. Electrons are expected to have *C*2 > *C*1, therefore all the particles below the line are assumed to be electrons.

Čerenkov light yield. In our small detector we have measured about 50 Čerenkov photoelectrons per deposited GeV. This number is comparable with the results from previous detectors already mentioned (about 30 Č.p.e. per GeV in BGO [3] and about 60 Č.p.e. per GeV in PbWO crystals doped with molybdenum [4]). Our result suggests that the tile readout could be interesting for dual readout calorimeters.

For a full containement electromagnetic calorimeter with the same sampling used in this test, the statistical contribution to the resolution from the Čerenkov photo-statistics should be about $14\%/\sqrt{E}$, *E* in GeV, that is similar to the sampling term, about $16\%/\sqrt{E}$, mainly determined by the thickness of the lead tiles.

In our prototype we expect a large and non uniform attenuation of the collected Čerenkov yield in the long light guides from the quartz tiles to the PMTs that adds to the loss for internal reflections inside the quartz tiles. In a real electromagnetic calorimeter a thinner sampling and a more efficient collection of the Čerenkov photons could give a consistently better resolution.

In a further version of this type of detector, the quartz tiles could be replaced with plastic tiles or with wave length shifter tiles. In the second approach the Čerenkov photons are promptly absorbed and the wave shifted light is emitted isotropically; this would improve the light collection at the sides of the Čerenkov radiating tiles. The signal collection with fibers embedded in the tiles could also be considered.

While the technique studied in this paper represents a possibility to extend the dual readout with tiles to an electromagnetic calorimeter in front of an hadronic calorimeter, one could imagine the same dual readout also in large hadronic calorimeters.

Acknowledgments

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