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Beam test results of a Silicon-PhotoMultiplier based Dual-Readout calorimeter module

Detectors for future experiments in high energy physics have to provide extreme precision in reconstructing trajectories and energies of both isolated particles and jets springing off the colliding beams. The energy measurement performed for hadronic showers is typically worse than the ones for electromagnetic showers mainly due to the event-by-event electromagnetic fraction (f_{em}) fluctuations, unless measured. Following the Dual-Readout calorimetric technique, which reconstructs f_{em} through the simultaneous measurement of the scintillation and the Cherenkov light produced by hadronic showers, a first Silicon PhotoMultiplier (SiPM) Dual-Readout calorimeter module was designed, constructed and tested on beam. An overview of the latest beam test results is reported together with the R&D program required to move towards a prototype conceived as a building block for a calorimeter that could be used in detectors at future accelerators.

Dual-Readout calorimetry

Shower induced by hadrons are made of two components:

Electromagnetic component: electrons, positrons, photons (from π^0, η^0 decays)

Non-electromagnetic component: (Average values in lead)
charged hadrons (20%), nuclear fragments (25%), neutrons (15%), *invisible energy* (40%)

Usually, the calorimeter response to the two components is different (non compensation): $\frac{h}{e} \neq 1$

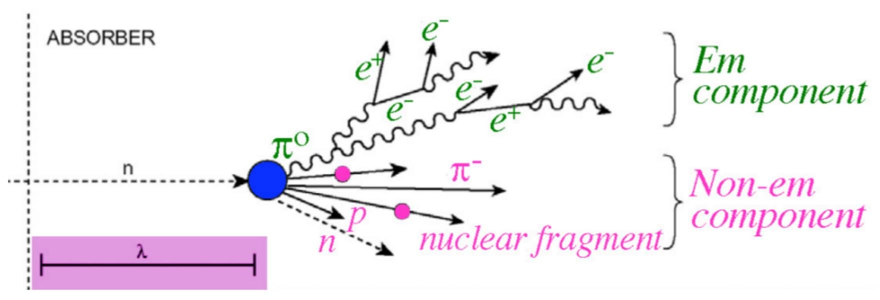
The electromagnetic fraction, i.e. the fraction of the shower energy deposited by the electromagnetic component, has an asymmetric distribution and increases on average with the energy.

Non compensating calorimeters:

- have a resolution spoiled by fluctuations between these two components
- are non linear detectors
- have a non-gaussian response

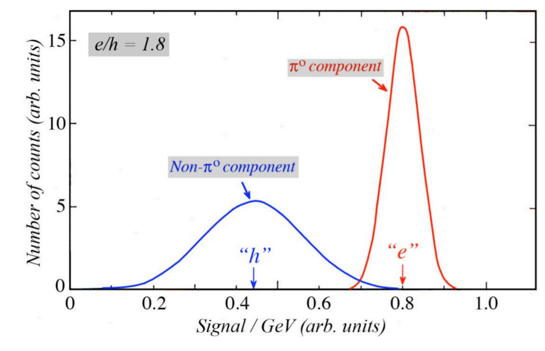
In a dual-readout fibre sampling calorimeter it is possible to measure, event by event, the electromagnetic fraction by means of two signals:

C: Cherenkov photons produced in clear fibres
S: Photons produced in scintillating fibres

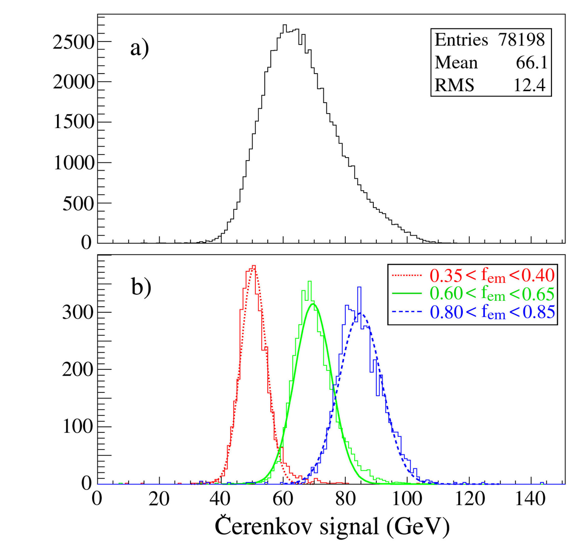


After a calibration with electrons, signals are given by:

$$S = E\left[f_{em} + (h/e)_S(1-f_{em})\right]$$
$$C = E\left[f_{em} + (h/e)_C(1-f_{em})\right]$$
$$\frac{C}{S} = \frac{f_{em} + (h/e)_C(1-f_{em})}{f_{em} + (h/e)_S(1-f_{em})}$$
$$E = \frac{S - \chi C}{1-\chi} \qquad \chi = \frac{1-(h/e)_S}{1-(h/e)_C}$$



100 GeV Pions

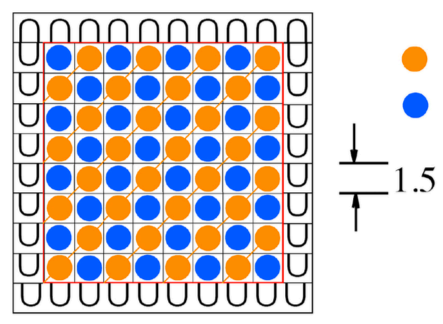


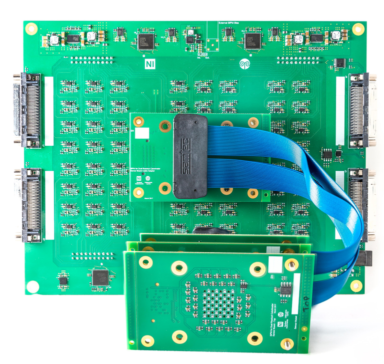
Akchurin N., et al., Nucl. Instr. and Meth. A 537, 537 (2004)

Beam test results

The brass (Cu^{260}) calorimeter used for the beam test is 112 cm long, with a lateral cross section of 15 x 15 mm². The active part is composed of 64 optical fibres, 32 scintillating (Kuraray SCSF-78) and 32 clear plastic (Mitsubishi SK40). The effective radiation length (X_0) is 29 mm while the Molière radius (R_M) is 31 mm. The module is thus 39 X_0 deep and has an effective radius of 0.22 R_M. According to Geant4 simulations, the em shower energy containment is ~ 45%. Each fibre is interfaced to a SiPM. Sensors are mounted, in a chessboard-like arrangement, on a two-tier board, providing individual bias and on-board temperature measurement. The mother board hosted 64 DC-coupled amplifiers with a 1μs shaping time. The channels are read out with two Multichannel Analog to Digital Acquisition systems (MADA) [1]. Each board integrates 32 channels, with 80 MS/s and 14-bit ADCs, performing real-time charge integration.

The beam tests were performed at the H8 beam line of the Super Proton Synchrotron at CERN. Electrons and muons beams with different energies (from 6 GeV to 125 GeV) were used to qualify the detector response [2].





ADVANTAGES OF SiPM

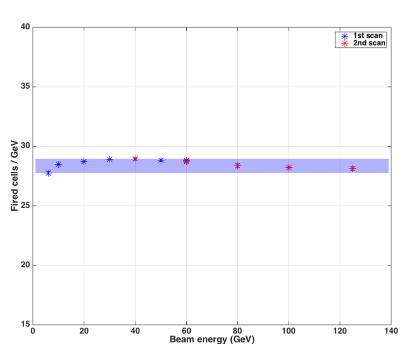
- compact readout
- possible longitudinal segmentation
- operation in a magnetic field
- higher photon detection efficiency (PDE)

POSSIBLE DRAWBACKS

- response non-linearity
- signal saturation
- optical crosstalk between scintillating and Cherenkov fibres

HAMAMATSU S13615-1025	
Sensitive area	1×1 mm²
Cell pitch	25 μm
No. of pixels	1584
Peak Photon Detection Efficiency	25%
Breakdown voltage V_{br}	53 V
Recommended operational voltage V_{op}	V_{br} + 5V
Gain at V_{op}	7×10^5
Dark Count Rate at V_{op}	50 kps
Optical Crosstalk at V_{op}	1%

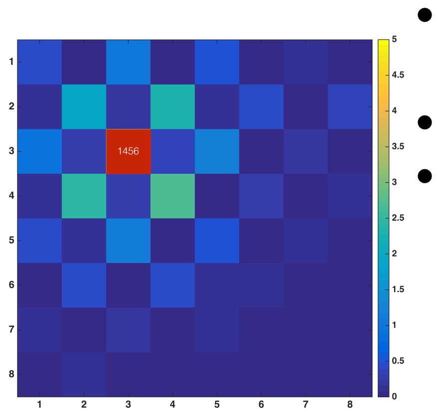
CHERENKOV LIGHT YIELD



- ~ 28.6 ± 0.4 C fired cells/GeV (25% PDE).
- Correcting for the shower containment (~ 36%) and the optical crosstalk of the S fibres: **69 ± 5 fired cells/GeV**.
- The expected stochastic term in em resolution becomes ~**10%/√E**.

OPTICAL CROSSTALK BETWEEN FIBRES

A direct measurement was performed with a sub-nanosecond light pulse (using a PicoQuant PDL 800).



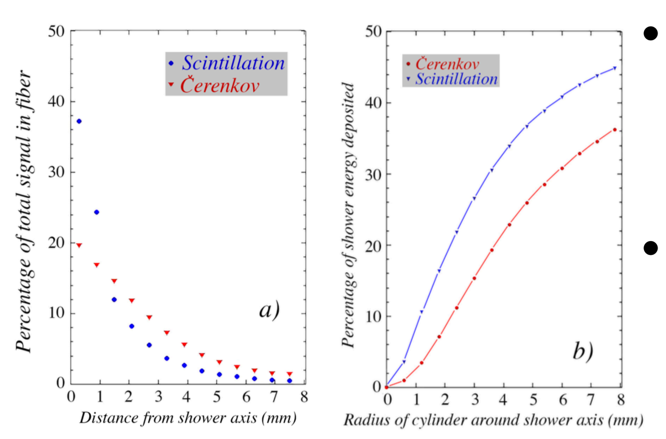
- Only one uncovered S fibre was illuminated.
- All 32 C signals were recorded.
- The optical crosstalk for each SiPM was measured to be:

0.3% ± 0.1%

of the scintillation signal.

SHOWER PROFILES

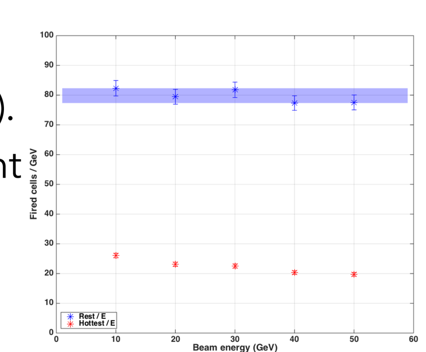
The possibility of separately reading each fibre allows to sample EM showers with a millimeter granularity.



- Half of the energy is deposited within few millimeters from the shower axis.
- The C light, produced by early shower component, falls outside the fibre numerical aperture.

SCINTILLATION LIGHT YIELD

- Saturation and non-linearity response.
- ~ 108.4 ± 0.9 S fired cells/GeV (2% PDE).
- Correcting for the shower containment (~ 45%) and normalized to 25% PDE:
  3200 ± 200 fired cells/GeV.
- ~ 50 times larger than the C signal.



Next steps

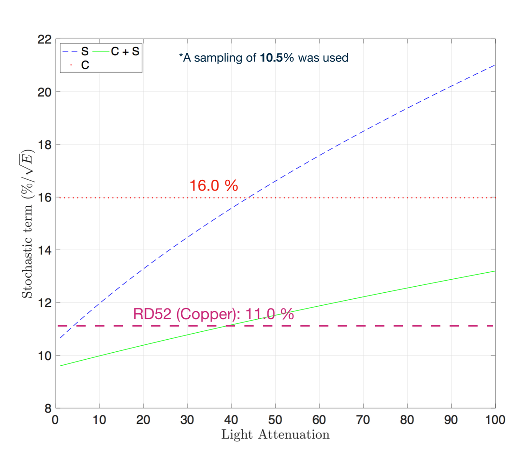
This first test demonstrated the feasibility of a SiPM-based readout, but it also pointed out some issues:

- Since the dual-readout method requires a full separation between Cherenkov and scintillating signals, actions for a further reduction of **the optical crosstalk** are envisage (**fibre insulation**).
- The **Cherenkov light yield** is a limiting factor for the energy resolution of this type of calorimeter. The results are very promising and could be further increased by adding an **aluminized glass mirror** at the upstream ends of Cherenkov fibres (an increase of the light yield of at least 50% is expected).
- **Saturation and non-linearity response** of the sensors, due to the high **scintillation light yield** are currently a significant limitation. The problem will be tackled:
  - Increasing the **dynamic range** of the sensor using SiPM with more total number of cells (i.e. 10 μm pitch, with 10000 cells).
  - Reducing the number of impinging photons using **yellow optical filters** between scintillating fibres and sensors. These filters selectively absorb the blue component, prone to self-absorption. So with the appropriate spectral response, filter will also improve the fibres response uniformity [3].

The necessary steps to perform a full prove of concept are:

- Some tests about the possibility of electrical **grouping** more than one sensor signal will be performed. This allows to reduce the number of channels to be readout.
- Electrical grouping also requires to find an **optimal readout electronics** solution in terms of ASICS, FPGA, etc.
- A long term step should involve a **calorimeter module sufficiently large** (simulations indicate that lateral containment at the 90% level requires an effective module radius of at least 50 mm, 1.6 R_M) to make leakage fluctuations negligible compared to the envisaged energy resolution.

LIGHT ATTENUATION EFFECT ON EM RESOLUTION



- Fluctuations in the number of fired cells/GeV increase the stochastic term in the em resolution.
- This contribute becomes more important with the increasing of the light attenuation.
- The optimization in term of light attenuation and sensor occupancy has to be found.

[1] http://www.nuclearinstruments.eu/sipm.html
[2] M. Antonello et all., arXiv: 1805.03251
[3] F.J. Hartjes and R. Wigmans, Nucl. Instr. and Meth. A277 (1989) 379-385

All the DREAM/RD52 publications are available at:
http://www.phys.ttu.edu/ dream/index.html