Dual-readout fibre-sampling calorimetry with SiPM light sensors

Lorenzo Pezzotti$^{1,2,*}$, Roberto Ferrari$^2$

1 Università degli Studi di Pavia, Pavia, Italy
2 INFN Sezione di Pavia, Italy

Massimiliano Antonello$^{3,4}$, Massimo Caccia$^{3,4}$, Romualdo Santoro$^{3,4}$

3 Università degli Studi dell’Insubria, Como, Italy
4 INFN Sezione di Milano, Italy

E-mail: lorenzo.pezzotti01@universitadipavia.it

Abstract. In this paper we present the most significant testbeam results of a dual-readout fibre calorimeter module equipped with silicon photomultipliers (SiPMs) to sense the scintillation and Cherenkov light signals. The main challenges of this detector are the minimization of the optical crosstalk between the two signals and the potential saturation of the digital SiPM-based readout. Both topics have been investigated with encouraging results. As a by-product of this extremely granular readout, the lateral profile of electromagnetic showers was sampled with an unprecedented precision close to the shower axis and significant differences were observed between the scintillating and Cherenkov signals.

1. Introduction

Hadronic showers develop an electromagnetic component (from neutral mesons such as $\pi^0$ and $\eta^0$) and a non-electromagnetic component that are sampled with very different sensitivities (“non compensation”) in traditional calorimeters. The large non-symmetrical fluctuations in the two components largely dominate the detector response resolution. Overcoming this limitation is the most important goal of calorimetry at future leptonic colliders. As a matter of fact, for a significant measurement of the Higgs boson couplings to the IVBs, it is mandatory to statistically separate the four-jet final states from $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$, where the only discriminant is the $W/Z$ invariant mass. This requires to reconstruct the IVB masses with a resolution of $3 - 4$ GeV, i.e. with an energy resolution of $\approx 30\%/\sqrt{E}$.

Dual-readout calorimetry is a technique able to overcome the non-compensation problem through the detection of two, independent, scintillation and Cherenkov light signals. The former is correlated with the whole energy deposition in the calorimeter while the latter provides a signal almost exclusively related to the electromagnetic component. The combination of the two allows to estimate, event by event, the electromagnetic fraction and correctly reconstruct the primary-hadron energy. The expected energy resolution for single hadron detection, estimated through simulations to be better than $\approx 40\%/\sqrt{E}$, together with the excellent particle identification capability, makes a dual-readout fibre-sampling calorimeter one of the most promising options for future leptonic colliders. The feasibility of this idea has already been demonstrated with several test
beams and detailed overviews on dual-readout calorimetry can be found in [1] and [2]. A dedicated R&D project recently started to address the issues that need to be solved for the construction of a real detector at $e^+e^-$ colliders. The first goal was to equip such a detector with a new SiPM compact readout. These solid state light detectors offer specific advantages with respect to traditional photomultipliers (PMTs):

- The SiPM is extremely compact and it is directly coupled to each fibre, thus eliminating the forest of optical fibres that extends for $\approx 30$ cm before reaching the PMTs.
- The compact readout allows to separate the calorimeter into longitudinal segments, if desired.
- SiPM are magnetic field insensitive, unlike PMTs.
- If each SiPM is readout independently, the calorimeter reaches an unprecedented spatial resolution (less than a millimeter).
- The quantum efficiency for single photon detection can be considerably increased with respect to PMTs. This is especially important for the Cherenkov light detection where the intrinsically low yield has proven to be a limiting factor for both electromagnetic and hadronic energy resolution.

On the other hand, SiPMs behave like digital detectors prone to saturation leading to a non constant response of the calorimeter. Since the SiPM-based readout collects light from a grid of close fibres and the two types of signals differ by about a factor 60, avoiding any possible contamination of the Cherenkov signal with light coming from the scintillation channel (optical crosstalk) is required.

To investigate all these aspects a first module, with a SiPM single-fibre readout, was designed, constructed and tested with beams at the CERN H8 line. All the results obtained with this detector are extensively reported in [3].

2. The detector
The calorimeter used consisted of a 112 cm long brass (Cu260) module with a lateral cross section of $15 \times 15$ mm$^2$. The active area was about $1.2 \times 1.2$ cm$^2$ and housed 32 scintillating fibres and 32 clear (Cherenkov) fibres in a chessboard-like geometry, Fig[1,2].

![Figure 1](image1.png)

**Figure 1.** Schematic view of the 64 optical fibres housed in the brass structure. Image from [3].

![Figure 2](image2.png)

**Figure 2.** The module front face with scintillating fibres lighted up from the rear end.

With an effective Moliere radius ($R_M$) of 31 mm and a radiation length ($X_0$) of 29 mm, the calorimeter was 39$X_0$ deep. According to GEANT4 simulations the electromagnetic shower containment was, on average, 45% of the primary electron energy. In order to exclude optical crosstalk of scintillation photons being detected as Cherenkov ones,
SiPMs were mounted on a two-tier structure where the 32 Cherenkov fibres were coupled to the SiPMs on the first plane, while the other 32 scintillating fibres were guided through holes in the first plane and readout on the second (back) tier. An exploded view of the two-tier readout is shown in Fig[3,4].

We used the HAMAMATSU S13615-1025 sensors featuring an active area of $1 \times 1 \text{ mm}^2$ and a pitch of 25 $\mu \text{m}$, resulting in a total number of 1584 active cells. The SiPMs used to readout the scintillating fibres were operated at 0.5 V over breakdown resulting in a photon detection efficiency of 2%. This non-optimal condition was needed to avoid saturation effects discovered especially in the “seed” fibres. The SiPMs coupled to the clear (Cherenkov) fibres were operated at nominal bias voltage and the typical detection efficiency of $\approx 25\%$.

The two-dimensional imaging properties of this calorimeter detecting electrons and muons are illustrated in Fig[5].

![Figure 3. Exploded view of the two-tier structure readout board. Image from [3].](image1)

![Figure 4. Optical fibres exiting the calorimeter and entering in the two-tier structure readout board.](image2)

![Figure 5. Event display of the 64 SiPMs connected to the scintillating fibres. Signals from Cherenkov fibres not included. Image from [3].](image3)
3. Experimental results

3.1. Optical crosstalk

Due to the intrinsic large difference in light yields between the scintillation and Cherenkov signal, it is mandatory to measure potential optical crosstalk originated by photons in the scintillation fibres being detected as Cherenkov photons in the others.

A first method, performed in the lab, used an LED: we illuminated a single scintillating fibre from the front face while masking all the other fibre tips. At the same time we recorded all the 64 light signals. The average recorded signal is shown in Fig[6].

![Figure 6](image)

**Figure 6.** Average signal recorded in all the 64 sensors as a result of the illumination of one scintillating fibre with a large light pulse ($\simeq 1400$ fired cells, red cell). Image from [3].

When a scintillating fibre was illuminated, no matter which one it was, the sum of the fired cells in the 32 Cherenkov fibres had a mean value of 0.3% of the scintillation signal, with an rms of 0.1%. This set an upper limit to the crosstalk measurements because the possibility that direct light from the LED was entering in the masked fibres could not be excluded.

A second method, performed at the CERN beam line, used muons: these particles produce different, well predictable, signals in the two channels and any difference from the expected values can be ascribed to crosstalk contamination. A detailed explanation of the procedure is reported in [3]. At the end of the analysis this method set an upper limit to the optical crosstalk as 0.4% of the scintillation signal in good agreement with the result obtained with the LED method.

3.2. Light yield and saturation

SiPMs offer the possibility to count the fired cells, thus making the calibration of the signals from electromagnetic showers straightforward. To estimate the signal light yield a detailed simulated scan of the electromagnetic energy containment was performed with GEANT4. The electromagnetic energy containment is estimated at the level of 45% independently of the electron energy, Fig[7(a)].

**Cherenkov light yield**

Fig[8] shows the average number of the Cherenkov photoelectrons (Cpe) detected, $\simeq 28.6$ Cpe/GeV, as a function of the beam energy. This value was constant within 2% in the range 6 – 125 GeV. Since the average energy containment is independent of the electron energy, this is a direct indication that there was no saturation in the Cherenkov signals. After accounting
for the energy containment and the optical crosstalk, we estimated a Cherenkov light yield of 54 ± 5 photoelectrons per GeV deposited energy, almost two times larger than what measured with PMTs.

Figure 7. Simulated average fraction of the shower energy deposited in the calorimeter as a function of the impact point for 10 GeV and 100 GeV electrons. Results for electrons entering the calorimeter along the direction of the fibres (a) or at an angle of 0.2° in both the vertical and horizontal plane (b). Image from [3].

Figure 8. Measured average number of Cherenkov photoelectrons divided by the electron energy, as a function of the electron energy. Image from [3].

Scintillation light yield
Dealing with scintillation light was a major concern for the SiPM readout. In order to exclude saturation, SiPMs coupled to the scintillating fibres where operated at voltage over breakdown resulting in a photon detection efficiency of ≃ 2%. In addition, when the SiPMs are illuminated with high fluxes of photons it is necessary to account for the possibility that more photons hit the same cell at approximately the same time, thus resulting in a single photon detection. This may be fixed with an occupancy correction for which the following equation represents a reasonable approximation:

\[ N_{\text{fired}} = N_{\text{cells}} \times [1 - \exp(-\frac{N_{\text{photons}} \times PDE}{N_{\text{cells}}})] \] (1)

where \( N_{\text{fired}} \) is the number of fired cells, \( N_{\text{cells}} \) is the actual number of active cells, \( N_{\text{photons}} \) is the number of photons hitting the SiPM and \( PDE \) is the SiPM photon detection efficiency.

Fig[9] shows the average scintillation signal, divided by the electron energy, as a function of the energy, both for the “hottest” fibre and the other (31) fibres.

It is evident how, after the correction, non linearity is affecting only the “hottest” fibre while the remaining 31 exhibits a linear response in the 10 – 60 GeV energy range. After correcting for the average electromagnetic energy containment and the 12.5 times different photon detection efficiency, we concluded that, at a photon detection efficiency of 25%, we would reach a scintillation light yield of 3200 ± 200 photoelectrons per GeV deposited energy. This is ≃ 60 times larger than the Cherenkov one.

Even if R&D work is still needed in order to further reduce the optical crosstalk and find a more suitable SiPM-based solution for the scintillation light detection, these encouraging results demonstrated the possibility to adopt SiPMs to perform dual-readout calorimetric measurements.
4. Is it a plus?

The ultra granular SiPM readout offers the possibility to sample electromagnetic showers, very close to the shower axis, in great detail. In the following, we describe the procedure we adopted. For every event the center of gravity \((\bar{x}, \bar{y})\) was estimated with the energies \(E_i\) deposited in the 32 fibres \((x_i, y_i)\) as:

\[
\bar{x} = \frac{\Sigma_i x_i E_i}{\Sigma_i E_i}
\]
\[
\bar{y} = \frac{\Sigma_i y_i E_i}{\Sigma_i E_i}
\]

The radial distance \(r_i\) between each fibre \(i\) and the shower axis was then reconstructed as:

\[
r_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}
\]

In so doing the lateral shower profile, for both signals, could be computed by averaging the signal in an individual fibre as a function of \(r\). Fig[10] shows the computed lateral shower profiles both from data, Fig[10a], and GEANT4 simulation, Fig[10b].

Both data and simulations clearly indicate a remarkable difference between the profiles measured by the two types of fibres. The Cherenkov light is much less concentrated in the first millimeters than the scintillation light. This is due to the fact that the early, very collimated, stage of the shower development is poorly sampled by the Cherenkov channel since the Cherenkov photons emitted there fall outside the numerical aperture of the fibres.

In Fig[11] we sum the signals from individual fibres located at the same \(r\) and plot the resulting average value. We call this the radial shower profiles. This clearly indicates the extremely sharp nature of electromagnetic showers: e.g. Fig[11b] shows that 10% of the entire shower energy is deposited within one millimeter from the shower axis, hence contributing to the signal of a single fibre.

This extremely collimated nature of electromagnetic showers may lead to spectacular results in a calorimeter able to sample showers with a millimetric precision. Fig[12] shows the result of three electrons entering the SiPM fibre calorimeter very close to three different fibres. Since the angle of incidence was exactly 0.0° each electron was oversampled in a single fibre due to the channeling effect. As a result, in an area of \(\simeq 1.2 \times 1.2 \text{ cm}^2\) three peaks are clearly separated. Another
Figure 10. Lateral profiles of electromagnetic showers developing in the brass dual-readout fibre calorimeter. Results from test beam data (a) and GEANT4 (b). Image from [3].

Figure 11. Radial profiles of electromagnetic showers in the brass-fibre dual-readout calorimeter, measured separately with the Čerenkov and the scintillation signals (a). The fraction of the shower energy deposited in a cylinder around the shower axis as a function of the radius of that cylinder, measured separately with the Čerenkov and the scintillation signals (b). Image from [3].

Benefit of this ultra granular readout is the possibility to identify electromagnetic showers coming from a $\pi^0$ (giving two $\gamma$'s) and from a single electron or $\gamma$. Fig[13a] shows a simulated event display of a 50 GeV electron induced shower and of a 100 GeV $\pi^0$ induced shower, with the $\pi^0$ decaying 2 m upstream of the calorimeter front face, Fig[13b]. As a result, the two $\gamma$’s from the $\pi^0$ decay are clearly recognizable.
**Figure 12.** Event display of three electrons entering the calorimeter very close to three different fibres. Shown are signals from scintillating fibres only, Cherenkov fibres are left white. Result from GEANT4 simulation.

**Figure 13.** Event display of a 50 GeV electron shower (a) and the two electromagnetic showers produced by the two $\gamma$'s from the decay of a $\pi^0$ produced 2 m upstream of the calorimeter front face (b). Result from GEANT4 simulation.

**5. Conclusion**

With the promise of reaching the ultimate resolution in hadronic energy measurements without being spoiled by all the “traditional” compensating calorimeter drawbacks, dual-readout calorimetry is one of the most interesting options for high precision experiments at future leptonic colliders. In this paper we presented the main benefits of a new ultra granular SiPM-based readout: the Cherenkov light yield, a major limiting factor for electromagnetic and hadronic measurements, was increased by a factor 2 with respect to PMTs and the electromagnetic showers were sampled, close to the shower axis, with a very high two-dimensional spatial resolution. The main possible problems related to the use of SiPMs, namely optical crosstalk between scintillating and Cherenkov signals and signal saturation, were studied in detail and the feasibility of using SiPMs to perform dual-readout calorimetric measurements was successfully demonstrated.

**References**

[1] S. Lee, M. Livan, R. Wigmans, Dual-Readout Calorimetry, Rev. Mod. Phys. 90 (2018) 025002.

[2] R. Wigmans, Calorimetry - Energy Measurement In Particle Physics, second ed., in: International Series of Monographs on Physics, vol. 168, Oxford University Press, 2017.

[3] M. Antonello, et al., Tests of a dual-readout fiber calorimeter with SiPM light sensors, Nucl. Instr. and Meth. in Phys. Res. A 899 (2018) 52.