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# Exposing a fibre-based dual-readout calorimeter prototype to beams of electrons

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As a part of the R&D for detectors to employ at future $e^+e^-$ colliders, a prototype of a fibre calorimeter with dual readout has been built and exposed to electron beams at DESY and CERN. With a length of 1 m and a lateral size of ~10 cm it almost fully contains electromagnetic showers. The central part of the detector was equipped with 320 Silicon Photomultipliers (SiPMs) spaced by 2 mm and individually read out, yielding a very high granularity sampling of the electromagnetic shower. The data-taking in 2021 was mainly devoted to testing the operation of the SiPMs in real beam conditions, and to the definition of the calibration procedure and the measurement of the light yield of the fibres. Preliminary results of the tests are discussed in the contribution.

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## 1. Introduction

The proposed future $e^+e^-$ circular colliders (such as for instance FCC-ee and CEPC) will run at centre-of-mass energies ranging from 90 to 365 GeV. The physics program includes a broad range of measurements, including precision measurements of the properties of the Higgs boson discovered at the LHC. A key instrumental ingredient for this program is the precise measurement of the hadronic decays of the $W$, $Z$ and Higgs bosons. The basic requirement is that the invariant mass of two jets from a decay of a 100 GeV resonance be reconstructed with 3-4 GeV resolution. This performance figure poses a serious challenge to the calorimetric measurement of jets, as typically a calorimeter system has a different response to the hadronic and electromagnetic components of a hadronic shower. The ratio of the two components fluctuates event by event thus limiting the achievable hadronic energy resolution.

A way of overcoming this limitation is the dual-readout technique, which relies on simultaneously measuring scintillation and Cherenkov signals from the shower. The scintillator signal is proportional to the full energy of the shower in the sampling material, whereas the Cherenkov photons are almost exclusively produced by the electromagnetic component of the shower. Based on the two independent measurements it is possible to determine the electromagnetic component of the shower event by event, and to achieve a precise measurement of the energy of the incoming hadron. This idea has been tested in a 20-year-long research programme, [1], which has demonstrated the viability of the concept based on the beam tests of several prototypes. The next step is the application of this idea to the design of a realistic calorimeter for a collider experiment. A simulation of a full $4\pi$ calorimeter based on this technique is documented in [2], where a hadronic energy resolution of $\approx 30\%/\sqrt{E}$ for single hadrons and $\approx 38\%/\sqrt{E}$ for jets was demonstrated.

As the first step in an R&D program aimed at building and testing on beam a module with full hadronic containment, an electromagnetic-sized dual-readout prototype was built and tested. The energy sampling is performed through plastic fibres embedded in a brass absorber. The core of the electromagnetic shower is read out with one SiPM connected to each fibre, thus providing a high-resolution image of the electromagnetic shower[3, 4].

In this paper, the first results of the analysis of electron data collected at DESY and at the SPS with this module will be discussed.

## 2. Experimental Setup

The prototype exposed to the beam in 2021 is shown in Figure 1. It is 1 m long with a cross section of $10 \times 10$ cm$^2$. The Moliere radius ($R_M$) is 23.8 mm while the effective radiation length ($X_0$) is 22.7 mm. It consists of 9 modules, each made of 320 brass capillaries (outer diameter = 2 mm and inner diameter = 1.1 mm) equipped, alternatively, with scintillating (BC-10 from Saint Gobain) and clear (SK-40 from Mitsubishi) fibres to allow the dual sampling. The external modules are instrumented with R-8900 PMTs. The scintillating and clear fibres are separated and bundled into two groups on the back side of each module to match the PMTs' window. A yellow filter (Kodak, Wratten nr 3, with a nominal transmission of $\approx 7\%$ at 425 nm and $\approx 90\%$ at 550 nm) is placed between the scintillating fibres and the detector to cut off the short wavelength component of the scintillation signal (standard configuration).

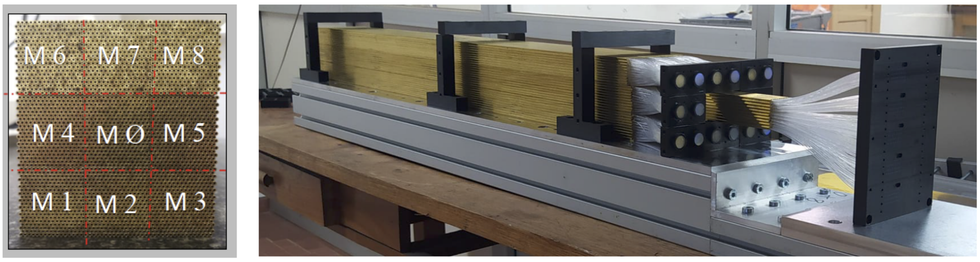


**Figure 1:** Front (**left**) and side (**right**) view of the em-size prototype before the connection to the light sensors (PMTs and SiPMs). The fibres from the external modules (M1-M8) are bundled to match the PMTs' window while the longer fibres from the central module (M0) are connected to a patch panel to be interfaced with SiPMs.

The central module (M0) has each fibre connected to a SiPM by Hamamatsu (S14160-1315 PS) with a sensitive area of $1.3 \times 1.3$ mm$^2$ read out independently. Since almost 10% of the entire energy is released within one mm from the core of the shower (1–2 fibres) [4], SiPMs with a wide dynamic range (i.e., 7284 cells, 15 μm pitch) were selected. The SiPM readout is based on the FERS-System produced by CAEN (A5202 boards). Each readout board operates 64 SiPMs. The signal produced by each SiPM feeds, at the same time, two charge amplifiers with tunable gains. The gain for the High Gain amplifier (HG) is almost 10 times larger than for the Low Gain (LG) one. This setup allows good resolution and linearity for signals from 1 to almost 4000 photo-electrons (ph-e). The prototype was exposed to beams at DESY and at CERN

### 2.1 DESY Setup Configuration

The trigger scheme was based on the coincidence of two scintillator counters placed in front of the calorimeter and the signal produced by the A5202 boards, running in self-trigger mode with a majority algorithm. Two independent data acquisition systems sharing the same trigger were run in parallel for the SiPM and the PMT and beam instrumentation. The offline synchronisation is performed by using the trigger ID. Data produced by electrons with energy ranging from 1 to 6 GeV were acquired and used in the analysis. The scintillating and the clear fibres were directly connected to the SiPMs without yellow filters, given the low energy of the electrons.

### 2.2 CERN Setup Configuration

The trigger was provided by the coincidence of two scintillator counters. A third scintillator with a hole of 10 mm was used as veto to determine the size of the beam. Two Cherenkov counters, a pre-shower detector and a scintillator positioned downstream of the calorimeter were used for particle identification, and two delay-wire chambers to determine the impact point on the calorimeter. The SPS electron beam had a large contamination of pions and the usage of a redundant particle identification system was essential for the offline selection of a pure electron beam. Data produced by electrons from 6 to 100 GeV are used in the analysis. The SiPM readout system was the same as the one used at the DESY test beam. Yellow filters were inserted between the scintillating fibres and the SiPMs (standard configuration).

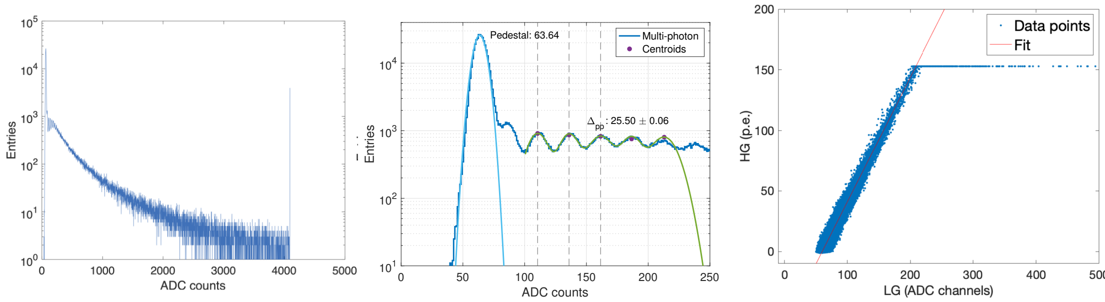


**Figure 2:** Left: HG spectrum of a SiPM for 6 GeV electrons. Centre: x-zoom of the same spectrum, showing the photoelectron peaks. Right: Correlation between the LG and the HG signals.

## 3. Test Beam Data Analysis

The two test beams were used for testing the readout system for the M0 module. A robust calibration procedure was defined, allowing the measurement of the light yield for both scintillation and Cherenkov signals for the prototype.

### 3.1 Equalisation and Calibration

The response of all SiPMs was equalised in the lab with an ultra-fast LED emitting at 420 nm before installation on the beam. Figure 2 left shows the typical HG spectrum measured by one SiPM in response to 6 GeV electrons at the DESY test beam. The pedestal, the multi-photon, and the ADC saturation are clearly visible. The procedure for measuring the conversion facto ADC counts to ph-e is as follows:

- The pedestal and the multi-photon are fitted with Gaussian functions. The conversion from ADC counts to ph-e is calculated from the mean value of the pedestal and the average peak-to-peak distance measured by fitting three consecutive peaks (Figure 2 centre).
- The HG values, converted in ph-e, are correlated to the ADC counts of the LG channel (Figure 2 right). The slope in the linear part is used to extract the ADC to ph-e conversion for the LG.

The procedure was repeated on a run-by-run basis, and run-to-run variations never exceeding 2% were measured for the baseline and peak-to-peak difference for all SiPMs. A single calibration constant per SiPM was therefore used for all the datasets analysed.

### 3.2 Energy calibration

In order to extract the calibration from ph-e to GeV, the signals for all the SiPMs are summed, separately for Cherenkov and scintillating fibres. Only electrons hitting the centre of the calorimeter are selected. To this effect, the energy-weighted $x$ and $y$ coordinates of the barycentre of each shower ($\bar{x}$ and $\bar{y}$) are calculated, and they are required to be in a square of $4 \times 4$ fibres ($\approx 8 \times 7$ mm$^2$) around the centre of the module. Figure 3 left shows the average number of detected Cherenkov and scintillation photons in the central module as a function of the electron beam energy, divided by the

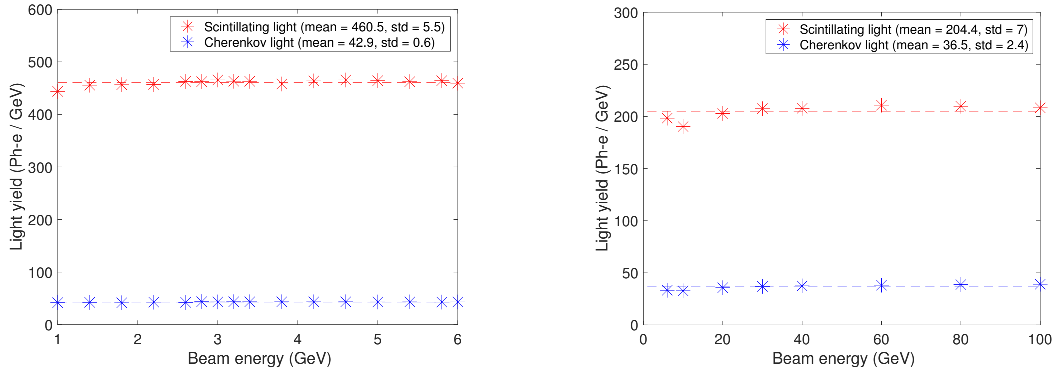


**Figure 3:** Average number of scintillation and Cherenkov photo-electrons/GeV detected by the central module as a function of the electron beam energy. Left: DESY results. Right: CERN results.

beam energy. In order to calculate the actual light yield, the values in the figure need to be corrected for the shower containment (≈72%), of the central module estimated with a detailed Monte Carlo simulation. After this correction ≈60 ph-e/GeV for the Cherenkov light and ≈640 ph-e/GeV for the scintillation light are obtained, in good agreement with a previous measurement performed with a small module [3].

Preliminary results for the SPS beam are shown in Figure 3 right. The events are selected as for the DESY test beam, but with additional requirements on the pre-shower and muon external detector to select a pure electron beam. After the correction for the shower containment a light yield for the scintillating fibres of 284 ph-e/GeV is measured. The reduction with respect to the DESY results is due to the yellow filters used to match the light yield with the dynamic range of the readout electronics. The Cherenkov light yield measured at CERN, shown in the same plot, is somewhat lower than the DESY measurement but compatible within the errors. A small additional light attenuation might have been caused by the transparent paper used between the clear fibres and the SiPMs.

### 3.3 Shower Shape and Comparison with Monte Carlo Simulation

The high granularity provided by the SiPM readout allows a detailed study of the shape of the electromagnetic shower in the calorimeter. A map of the energy deposited in each fibre of the calorimeter by a typical 6 GeV electron is shown in Figure 4 left.

This information has been used to validate the lateral shape of the shower development in the Monte Carlo simulation, as shown by the right plot in Figure 4. The variable $r_i$ is defined as the radial distance of each fibre $i$ from the barycentre of the shower, defined as $r_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$ where $\bar{x}$ and $\bar{y}$ are defined in the previous section and $(x_i,y_i)$ is the position of fibre $i$. The lateral shower profile is measured by averaging in radial bins of 1 mm the fraction of scintillation and Cherenkov signals and plotting them as a function of $r_i$. The Cherenkov signals have a wider shape, and this could be due to the fact that the Cherenkov light produced in the core of the shower (highly collimated at the beginning) falls outside the fibre numerical aperture [3]. The test beam data and the Monte Carlo simulation exhibit a good match over two orders of magnitude of energy deposition.

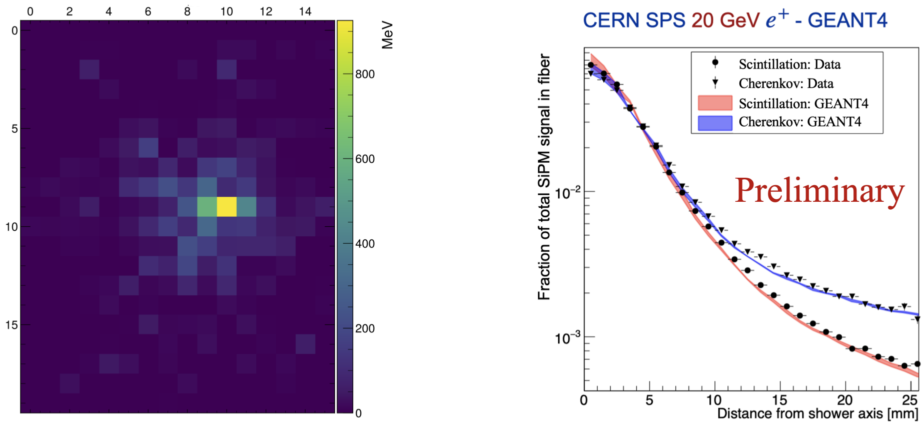


**Figure 4:** Left: Event display for the energy deposition of a 6 GeV electron in module M0. The colour in each box is proportional to the energy-calibrated signal recorded by each SiPM. Right: Lateral profile of showers produced by 20 GeV electrons in the calorimeter, separately for the scintillation and Cherenkov signals. The test beam data are compared to the results obtained with a Monte Carlo simulation that describes the CERN experimental setup.

## 4. Conclusions

An electromagnetic-size prototype with dual readout, partially equipped with SiPMs, was built and tested in electron beams at DESY and CERN in 2021. The aim was to test scalable solutions for the construction and the readout in view of a hadronic-sized module to be built in the near future.

The prototype was built using high-precision industrially produced brass capillaries, and an assembly solution for them was developed guaranteeing the required mechanical precision [5].

A new SiPM readout scheme was implemented and tested. It was possible to define a robust calibration procedure. Settings suitable for the SiPMs and the readout boards in use were identified, allowing the operation of the system in a linear regime up to high beam energies, while preserving access to the multi-photon spectra required for the calibration.

## Acknowledgments

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany) and at the Super Proton Synchrotron (SPS) at CERN.

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