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The Scintillator HCAL Testbeam Prototype

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The CALICE tile HCAL group has completed the analysis of data collected at the DESY electron test beam with a small scintillator steel hadron calorimeter prototype instrumented with 99 channels of novel SiPM photodetectors. The mechanical calorimeter design has been revised, and new front end electronics based on the CALICE ECAL architecture has been developed, for a 8000 SiPM channel cubic-meter prototype to be tested in hadronic beams. An overview on the systems design and construction status is given.

1. INTRODUCTION

The ambitious goal for the linear collider detector of a jet energy resolution of $30\%/\sqrt{E}$ is set by the mass splitting between W and Z bosons: they must be separable in their dijet final states. The particle flow (PFLOW) concept of optimized overall detector performance by individual particle reconstruction demands high spatial resolution in electromagnetic (ECAL) and hadronic (HCAL) calorimeters [1]. With the advent of Geiger mode solid state photodetectors high readout granularities can be realized with scintillators. The scintillator-based analogue HCAL is one option for an imaging hadron calorimeter, the other being a gaseous digital HCAL.

2. THE MINICAL EXPERIENCE

The Silicon photomultiplier (SiPM) [2] is a pixelated avalanche photodiode which provides a gain of $\sim 10^6$, comparable to that of vacuum phototubes. On a 1 mm^2 surface 1000 pixels operate independently in limited Geiger mode and produce a signal corresponding to the number of fired pixels. Due to its small size, high gain, low bias voltage (typically 50 V) and insensitivity to magnetic fields the device can be mounted directly on scintillator tiles for individual readout.

Only very recently SiPMs have become available from Russian industry in larger quantities. First experience with a 99 channel HCAL prototype ("minical") was gained in 2003 in the DESY positron test beam and has been reported at LCWS04, final results have meanwhile been published [3]. The minical is a sandwich structure with 2 cm steel absorber plates interleaved with 11 active layers, each containing 9 scintillator tiles ($5 \times 5 \times 5 \times 0.5\ \mathrm{cm}^3$) with SiPMs mounted directly on the tile and collecting the light via a circular wavelength shifting (WLS) fiber. The light yield of this tile fiber SiPM system was 25 ± 5 pixels per minimum ionizing particle (MIP).

The limited number of pixels on a SiPM introduces noticeable non-linearity effects; for 6 GeV electromagnetic showers the energy depositions in the shower core were ranging up to an equivalent of almost 100 MIPs per tile. The effects could successfully be corrected for on a channel-by-channel basis using a single well-measured SiPM response function and the light yield in terms of pixels per MIP for individual tiles. Such a light yield calibration requires the observation of single photo-electron signals, for which special front end electronics was connected. Fig. 1 shows the measured energy and resolution as a function of beam energy. The uncorrected data (open circles) exhibit the size of the non-linearity correction for the entire shower. The results compare well with those obtained with conventional multi-anode vacuum phototubes and with APDs (not shown here; see [4]). They are well reproduced by a Monte Carlo simulation which includes the detailed SiPM behaviour. Thus, after correction the saturation effects do not degrade the calorimeter linearity and resolution. The successful minical experience encouraged the group to proceed towards the construction of a cubic-meter sized prototype for hadron beam tests, based on the novel SiPM.

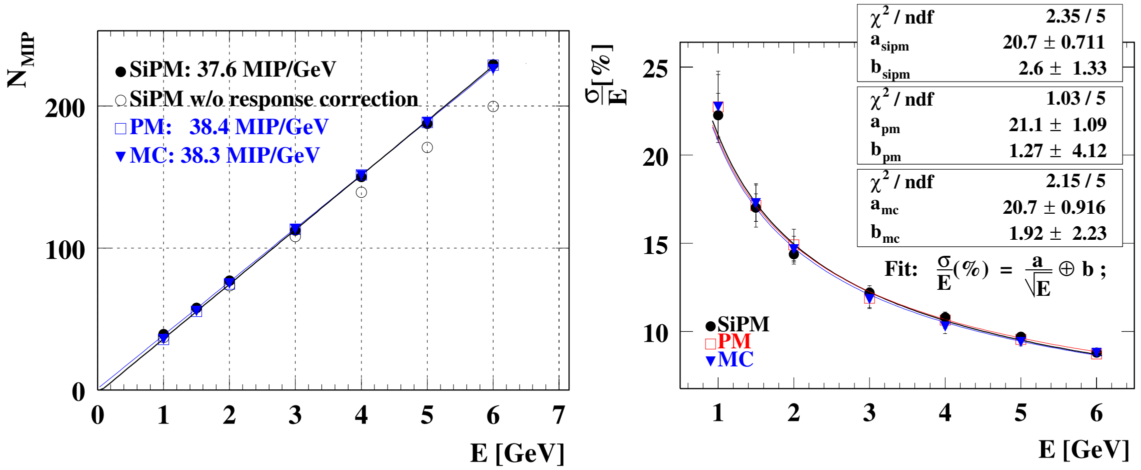

Figure 1: Minical linearity and resolution.

3. THE TESTBEAM PROTOTYPE

3.1. Overview

The goals of the HCAL beam tests are twofold: on the technology side, the aim is to gain large-scale, long-term experience with a SiPM readout detector and to identify critical operational aspects for further system optimization. On the physics side, the purpose is to collect the large data samples (order of 10^8 events) needed to explore hadron showers with unprecedented granularity, validate hadronic shower simulation models and develop PFLOW reconstruction algorithms. Due to the presently large model dependence of predictions for PFLOW-relevant shower properties [5] it is indispensable to base the further detector optimization on real beam data. In that respect the term "prototype" may be misleading: the aim is a "proof of principle"; technical solutions scalable to a full detector design are only partially addressed.

The basic tile size of the prototype was optimized with respect to particle separation capability [6] and found to be 3×3 cm^2. Such a small size is also suggested within the semi-digital approach [7] where one chooses a moderate granularity (relative to the 1 cm pad size proposed for the gaseous digital option) in conjunction with a two-bit, three-threshold readout. The calorimeter will thus allow to test the analogue and the semi-digital HCAL option with a single device.

In order to save channel count and cost, the high granularity is restricted to a 30×30 cm^2 30 layer core, surrounded by larger (6 and 12 cm) tiles. The total number of channels for 38 layers is still about 8000. This step of two orders of magnitude with respect to the minical represents a tremendous challenge for the industrialization of SiPM (and scintillator) production and quality control (Section 3.3). It also demanded a new integrated front end electronics concept for the readout in the combined (ECAL + HCAL) beam test and for the individual SiPM bias voltage adjustment (Section 3.2). A versatile calibration and monitoring system [8] and a modular mechanical design (Section 3.4) were required in addition.

This challenge is being met by a collaborative R & D effort with a rather high degree of task sharing; for an overview see Table I. For such a distributed effort a well structured software environment is essential. This is being developed on the basis of the inter-regional LCIO data model in close interaction with the ILC simulations and software group and presented in a separate talk [9].

The non-linearity of the SiPM response poses non-standard demands on the calibration system. It is foreseen to use the procedures established in the minical. However, with the short minical testbeam runs it had not yet been necessary to seriously address the issue of stability and monitoring. Since the SiPM response varies with temperature by about 5% / K, additional measures must be taken to ensure optimal physics performance over longer run periods. A redundant calibration and monitoring system [8] is foreseen, which is based on temperature measurement, on direct

Table I: Task sharing in the CALICE tile HCAL prototype effort

SiPMs	MEPhI
SiPM tile systems	ITEP
Module construction, LED light distribution	DESY
LED calibration electronics	Prague
Front end ASICs	LAL
Front end boards	DESY
DAQ	Imperial College, RAL
Absorber stack, movable table, slow control	DESY
Commissioning	DESY, Hamburg, MEPhI, later NIU, all

gain monitoring using the single photo-electron signal spacing, and on classical LED reference signals. It should also allow to control the long-term behaviour of the SiPM saturation effects.

3.2. Readout electronics

The HCAL prototype has a similar number of analogue readout channels as the CALICE silicon tungsten ECAL prototype, which eventually have to be integrated in a combined testbeam setup. The HCAL readout concept was therefore based on the same architecture, using the same back-end data acquisition and adapting the front-end electronics to the SiPM needs. The front-end consists of an 18-fold multiplexed pre-amplifier shaper sample-and-hold chain in a single ASIC (FLC-PHY3 [10]) and is followed by the VME back-end CALICE readout cards (CRC [11]) with 8 input ports, each port receiving the signals from 12 ASICs on 16-bit ADCs. The CRCs can run at 1 kHz instantaneous input rate, have sufficient on-board memory to buffer 2000 events and can process the data at an average event output rate of 100 Hz.

As there is no pipeline, the maximum trigger latency time is determined by the peaking time of the front-end shaper of about 180 ns. With such a long shaping time, the observation of single pixel SiPM signals is hampered by pile-up of noise signals occurring at a rate of 2-3 MHz. Thus, for calibration purposes, the preamplifier-shaper must switch to shorter peaking time and larger gain; for LED pulses trigger latency is not necessary. The new ILC-SiPM chip has a high degree of configurability of shaping parameters, see the block diagram in Fig. 2. The figure also shows a SiPM pulse height spectrum with well distinguishable single-pixel signals, recorded with the ILC-SiPM. The chip was developed, prototyped and produced in less than one year and is presented in more detail in [12]. The ASIC also contains for each of its 18 channels an 8-bit DAC for adjustment of the SiPM bias voltage in a 0-5 V range and thus solves the problem of supplying 8000 different and adjustable operation voltages to the calorimeter prototype.

The front end boards are arranged as motherboard plus piggy-back. The piggy-backs hold one ASIC each and the shift registers for its configuration, the base boards provide the connection to the SiPMs on one side and the interface to DAQ and power supplies on the other. One HCAL module can thus be connected to one CRC port, the whole prototype be readout with a less-than-half-populated VME crate. The same components (ASIC and boards) will also be used for the scintillator strip tail catcher [13] of the CALICE testbeam set-up, which is also read out with SiPMs.

3.3. SiPMs and scintillators

Until recently, the minical represented the world stock of SiPMs. After the testbeam run part of the sensors were used for long-term studies. No parameter variations were seen, albeit with limited statistics. This important issue will have to be re-addressed once the multi-channel electronics is available, allowing to operate and monitor larger numbers of sensors at their proper bias voltage.

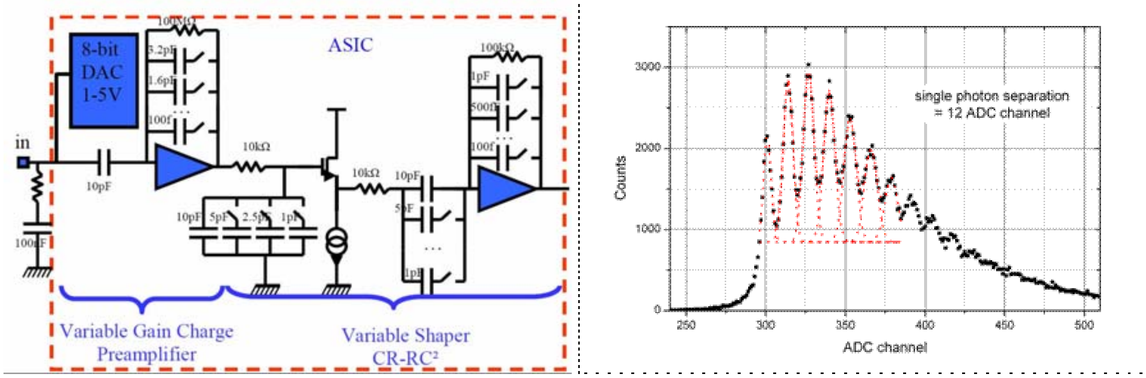

Figure 2: ILC-SiPM block diagram, SiPM pulse height spectrum with single pixel signals.

Mass production of SiPMs is still a pioneering endeavor. A first attempt to produce the quantity needed for the prototype failed, the performance was too much degraded due insufficient wafer quality. A second attempt was more successful and has a yield which will provide sensors for about half the prototype. Production of the remainder is still the source of a certain schedule risk.

The properties of the SiPMs for the prototype are the same as in the minical, except for the choice of a larger value for the quenching resistor (around 10 MΩ instead of 400 kΩ). This improves the pixel uniformity and reduces the sensitivity to the exact calibration light pulse shape, since it implies a larger pixel recovery time.

Quality control proceeds in several semi-automatic steps. While the basic functionality – light sensitivity at acceptable dark current – can be checked on the un-cut wafer in a probe station, the determination of the proper bias voltage working point and parameters for final selection can be done only after mounting the sensors on their support plate (see Fig. 3). The third stage is the determination of the actual light yield after assembly of the tile fiber SiPM system. After this procedure each system comes with its own complete data sheet which contains all parameters from dark rate to response function and is stored in a data base. Two examples – dark rate and inter-pixel cross-talk – are shown in Fig. 4 for a pilot batch of about 800 SiPMs. These two parameters determine the noise rate above a certain threshold, say 1/2 MIP. For the selected SiPMs, this rate corresponds to about one spurious hit per event in the prototype.

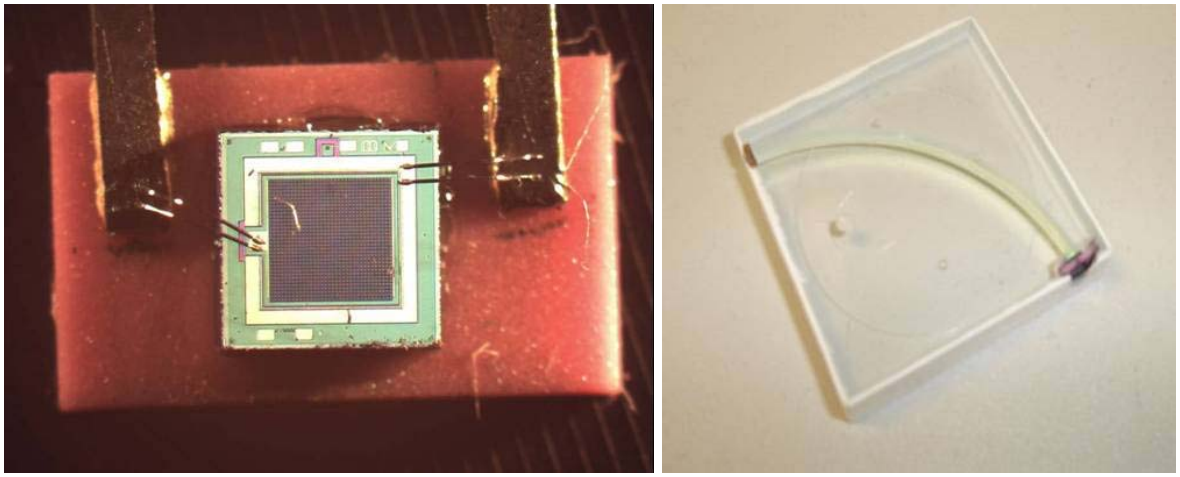

Figure 3: Tile and SiPM.

Scintillator production has been completed to a large extent. The 3 cm tile type is shown in Fig. 3. The tile edges have been matted by chemical treatment for diffuse internal reflection and suppression of optical cross-talk between

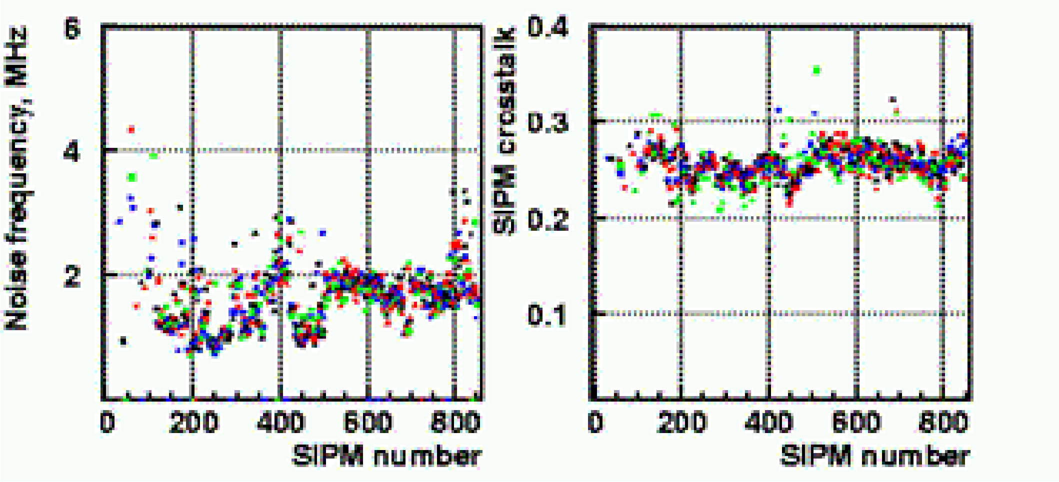

Figure 4: SiPM parameters dark rate and inter-pixel cross-talk vs. sensor serial number.

adjacent tiles ($< 2\%$). The light yield is presently adjusted to be 15 ± 1.5 pixels / MIP, a compromise between MIP signal-to-noise separation and dynamic range.

3.4. Module construction, mechanical structure

At the time of LCWS04, the 216 tiles for the first layer had been assembled while those for the second had been shipped. Fig. 5 shows the tile array laid out in the steel cassette. The size of the active area is 90×90 cm^2. In the next step of module assembly, the tiles are covered with a plastic (FR4) board which serves as a support for calibration light fibers and for the 1 mm micro-coax readout cables, which are connected to the SiPMs via small flexible PCBs. A fully assembled module with front end electronics connected is shown in Fig. 5 (right). The complete module will be inserted into the absorber stack structure, of which the parts have been constructed, and which is shown mounted on top of a moving stage in the design drawing of Fig. 6. The drawing shows the configuration set up for inclined beam incidence; the construction ensures that the beam still passes through the high granularity core in all layers. The stack and its support have been designed in a modular and flexible way which allows to adapt it for beam tests with other active modules, for example with resistive plate chambers for tests of the gaseous digital HCAL. Integration of the set-up into testbeam environments is under study now.

Figure 5: Scintillator tile layer, complete module with front end electronics.

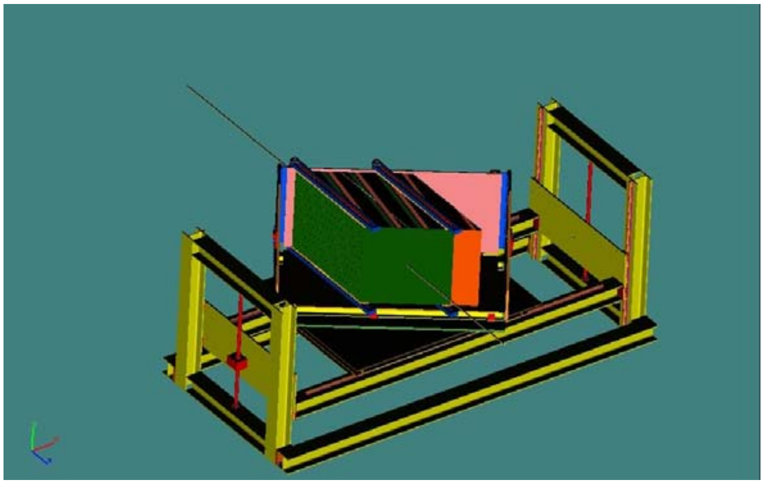

Figure 6: HCAL stack on its movable table.

4. CONCLUSION

The successful operation of the 99-channel "minical" has established the SiPM as photodetector for calorimetric applications. This opens up new possibilities for highly granular scintillator-based calorimeters. SiPMs are now becoming available in large quantities; a production and quality control chain has been set up and shows stable sensor properties. Construction and commissioning of an 8000 channel calorimeter prototype for combined ECAL and HCAL hadron beam tests is in progress, using a unified electronic readout concept. If all goes well, the system will be ready to collect data in 2006.

Acknowledgments

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