A scintillator based calorimeter with novel photodetectors

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http://polywww.in2p3.fr/flc/calice.html , http://www-flc.desy.de/flc/science/hcal/index.html

The precision physics program at a future Linear Collider (LC) requires reconstructing hadronic final states of heavy boson (W, Z, H) decays in multi-jet events. For this purpose a jet energy resolution of better than $30\%/\sqrt{E}$ is necessary. Monte Carlo simulations demonstrate that such a resolution can be achieved using a novel "particle flow" approach in which each particle in a jet is measured individually. In this approach the calorimeter must have very fine longitudinal and transverse segmentation. For hadron shower separation a transversal segmentation of about 3x3 cm^2 is needed. Such a granularity can be realized on large scale using scintillator tiles with wave length shifter (WLS) fibre light collection, individually read out by novel multi pixel Geiger mode photodiodes (the so-called Silicon photo-multiplier (SiPM)) as photodetectors, and it has been successfully tested in a first prototype.

The SiPM (Fig. 1) is a multi-pixel semiconductor photodiode with pixels joint together on a common silicon substrate. Each SiPM pixel operates independently in limited Geiger mode, under a common bias voltage $V_0+\Delta V$ of 10-20% above the breakdown voltage V_0 of typically 50V. The Geiger discharge is quenched when the voltage drops below V_0 due to an external resistor on each pixel which has a value of 100-200 kΩ. This resistor serves also as a decoupling element between individual pixels because the pixel RC value of ~10ns is considerably larger than the discharge time of less than 1 ns. The signal is determined by the charge accumulated on the pixel capacity of about 100 fF and does not depend on the number of primary photoelectrons. With ΔV of a few volts his leads to a signal of about one million electrons; i.e. the SiPM has a gain similar to that of vacuum photo-multipliers. The SiPM has an area of 1 mm^2 and contains 1024 pixels. Since all pixels work on a common load, the output signal is the sum of the signals from all fired pixels. The SiPM thus works as an analogue photodetector with a dynamic range determined by the number of pixels.

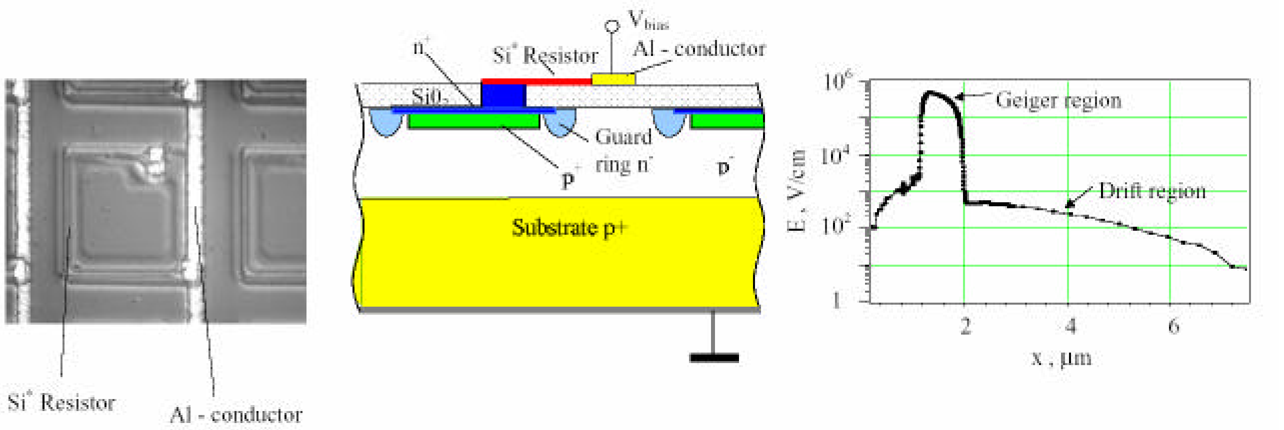

Figure 1 *Photograph of the SiPM surface (left; the depicted area is ~40 µm wide); schematic cross section (centre), electric field as a function of depth (right). .*

The SiPM photon detection efficiency e is a product of the quantum efficiency, the fraction of the SiPM surface covered by active pixels, and the probability for a photoelectron to initiate a Geiger discharge. The two latter factors increase with the excess voltage ΔV, yielding an efficiency as high as 20%. However, the noise rate and the inter-pixel cross talk also increase with ΔV, therefore we operated the SiPMs at a voltage corresponding to an efficiency of about 10-12%. The SiPM detection efficiency and the gain vary moderately with bias voltage and temperature; the relative changes of the resulting signal amplitude are 7% / 0.1V and -4% / K. The SiPM is not sensitive to magnetic fields, which was verified experimentally up to 5 Tesla. Long term stability is presently under study. Twenty SiPMs have been operated during 1500 hours at room temperature and five SiPMs were operated 170 hours at temperatures up to 90°C. No change in the parameters has been observed.

A small 108-channel calorimeter prototype has been built in order to gain experience with this novel technique. It is a steel-scintillator sandwich structure with 12 active layers interleaved between 2 cm thick absorber plates. The scintillator tiles with a size of 5x5x0.5 cm^3 have been produced in Russia using a moulding technique. A Kurarai Y11 double clad WLS fibre of 1 mm diameter is inserted into a circular groove without gluing. The SiPM is placed directly on the tile, with an air gap of about 100 µm between the fibre and the SiPM, and occupies less than 0.5% of the sensitive area (Fig. 2, left). The configuration has been optimized to provide a light yield of more than 20 photoelectrons for minimum ionizing particles (MIP), which is sufficient for precise channel by channel energy calibration. Fig. 2, centre, shows LED and β^- source (Sr) induced signals from such a tile. Single photoelectron peaks are clearly seen in the LED signals; the signals from the beta source are very similar to the MIP signals.

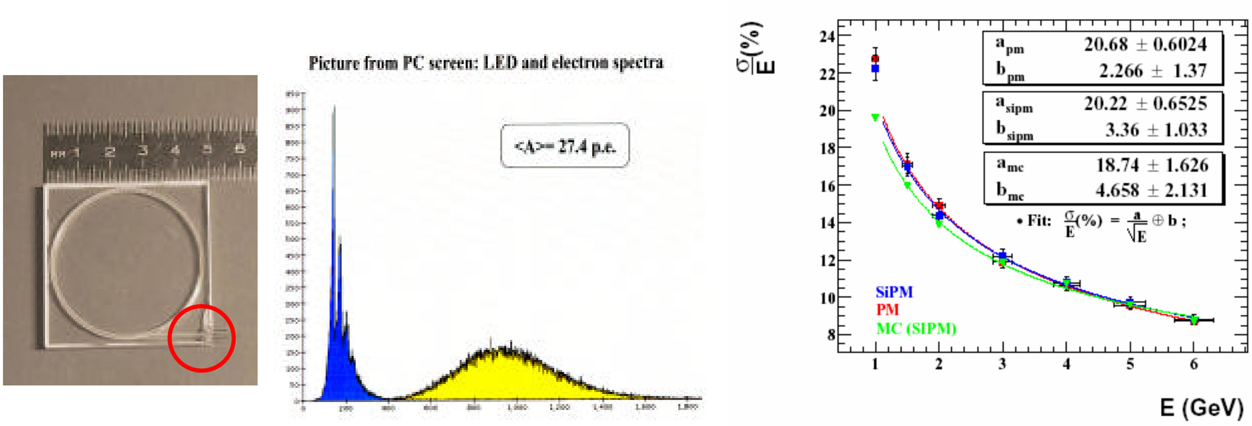

Figure 2: *SiPM mounted with WLS fibre on a scintillator tile (left), pulse height spectrum for irradiation with LED and* b^- *source (centre), hadron calorimeter prototype energy resolution for electrons, compared with that obtained with vacuum tubes, and with simulations (right).*

This hadron calorimeter prototype has been successfully operated in the DESY electron test beam at energies of 1 – 6 GeV. Non-linearity effects due to the limited number of pixels were noticeable in the shower core, but could successfully be corrected using the well-measured SiPM response function. Figure 2(right) shows the measured energy resolution as a function of beam energy. The data compare well with results obtained with conventional multi-anode vacuum phototubes which have been used with similar tiles in the same sandwich structure, and they are well reproduced by a Monte Carlo simulation which includes the detailed SiPM behaviour.

We are now constructing a $1m^3$ sized 8000 channel hadron calorimeter prototype with 3x3 cm^2 tiles in the centre. Partial instrumentation with avalanche photodiodes as alternative photodetectors is also foreseen. With this prototype we plan to establish the new technology on intermediate scale in an accelerator environment and to address operational issues such as calibration and long term stability. Hadronic shower data collected with unprecedented granularity will form a basis to validate and improve the simulations of shower development and to prove the “particle flow” approach, which to a large extent determines the architecture of LC detectors.

The described novel photon detection technique opens up new possibilities in scintillator-based particle detectors and has a rich potential for future use in other fields like radiation monitoring, detection of extended cosmic showers, and medicine.