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R&D for a highly granular SiW ECAL and analysis of beam test data

Thibault Frisson, on behalf of the CALICE Collaboration*
Laboratoire de L'accélerateur Linéaire (LAL), CNRS/IN2P3, Orsay, France
E-mail: frisson@lal.in2p3.fr

The CALICE collaboration is preparing large scale prototypes for highly granular calorimeters for detectors to be operated at a future linear electron positron collider. After several beam campaigns at DESY, CERN and FNAL, the CALICE collaboration has demonstrated the principle of highly granular Silicon-Tungsten electromagnetic calorimeters with a first prototype called physics prototype. The next prototype, called technological prototype, addresses the engineering challenges which come along with the realisation of highly granular calorimeters. This prototype will comprise 30 layers where each layer is composed of four 9×9 cm^2 silicon wafers. The front end electronics is integrated into the detector layers. The size of each pixel is 5×5 mm^2. This prototype enters its construction phase.

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*Speaker.

1. Introduction

The next machine after the LHC will be a linear electron positron collider (LC) at the TeV scale. This machine will allow high precision measurements to extend the scientific results of the LHC. There are two proposals for the linear collider: the ILC (International Linear Collider) and CLIC (Compact Linear Collider) with up to 3 TeV center of mass energy. The ILC is an international project for an e^+e^- linear collider with up to 1 TeV center of mass energy.

The physics goals of the LC requires excellent jet energy resolution and particle identification in the multi-hadronic final states [1]. The reconstruction of the final states of the e^+/e^- collisions will be based on so-called particle flow algorithms (PFA) [2]. The goal is to reconstruct every single particle of the final state using the combination of information from each sub-detectors. Particularly a perfect association of the signals in the tracking systems with those in the calorimeters is required. To meet these requirements the detectors need an unprecedented high granularity.

The CALICE (Calorimetry for the Linear Collider Experiments) collaboration [3] designs and studies electromagnetic and hadronic calorimeters for experiments at a futur LC. The employed technologies are also useful for non-LC experiments (like PAMELA and PHENIX) and for applications beyond the particles physics, like medical ones.

2. The Silicon Tungsten Electromagnetic Calorimeter

A Silicon Tungsten Electromagnetic Calorimeter (Si-W ECAL) is the baseline for both detector concepts, called ILD and SiD, proposed for the LC. The main role of the ECAL is to reconstruct photons even in the presence of close-by particles and to measure the energy of showers from neutral hadrons together with the hadron calorimeter (HCAL). The precision physics at the LC requires that the calorimeters remain inside the magnetic coil. Tungsten has a short radiation length ($X_0 = 3.5$ mm) and a small Moliere radius ($R_M = 9$ mm) which gives compact showers and allows an efficient separation of close particles. Tungsten also has the advantage to have a large interaction length ($\lambda_I = 96$ mm), compared to its X_0, which leads to a good separation between photons and hadrons. The silicon allow a thin and easily segmented readout detection system suited for high granularity. For the ILD baseline the ECAL should be made of 30 layers, leading to $24X_0$ in total, equivalent to one interaction length.

3. The Si-W ECAL physics prototype

The prototype was composed of 30 layers of silicon as active material, alternated with tungsten as absorber material. Each silicon layer has an active area of 18×18 cm^2, segmented into modules of 6×6 readout pads of 1×1 cm^2 each, giving in total 9720 channels. The silicon thickness is 525 μm [4].

The physics prototype was tested in 2006-2011 in DESY, CERN and FNAL facilities with $e^-, \pi, \mu, p (1 \rightarrow 180\,GeV)$. This prototype improved our understanding of the detector in terms of calibration, noise and performance. It gives good results for the signal over noise ratio (7.5:1) and energy resolution for electrons ($\sigma_E/E = 16.5/\sqrt{E}(GeV) + 1.1\%$) [5]. It also shows good particles separation which is a major point for the PFA [6]. Furthermore, the high granularity of the calorimeter offers unprecedented information to study hadronic interactions.

4. The Si-W ECAL technological prototype

Since 2007 a technological prototype of the Si-W ECAL is developed and tested. This prototype will be a proof of engineering feasibility of the project. Its size will be 3/5 of a barrel module of the ILD detector. A large mechanical structure made of tungsten-carbon reinforced epoxy (CRP) composite have already been produced and tested with success (see Fig. 1). The front-end electronics will be integrated inside the detectors layers (see Fig. 2 and Fig. 3) to keep compactness. A leak-less water system for has been developed for the technological prototype and tested successfully at an earlier mechanical demonstrator.

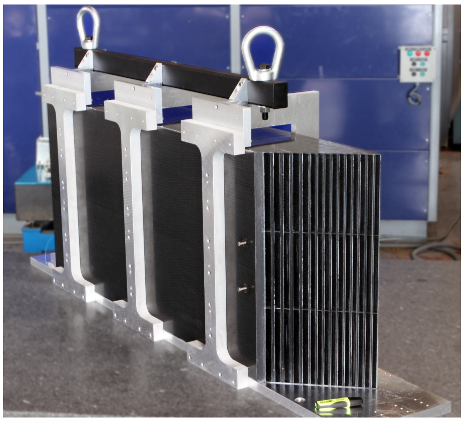

Figure 1: Mechanical structure of the technological prototype.

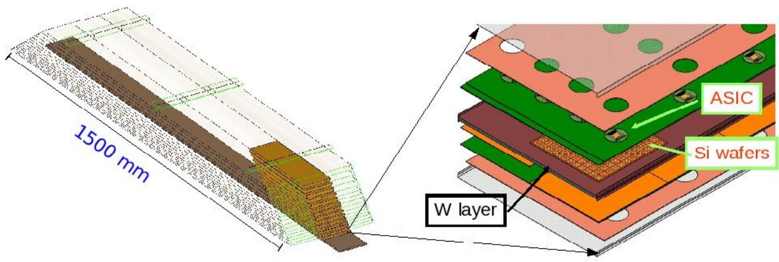

Figure 2: Left: Sketch of the layers inside the mechanical structure of the technological prototype. Right: Exploded image of one layer.

4.1 The Silicon Wafers

The silicon wafers are the active material of the detector. In the prototype, Si wafers of $9 \times 9\,\mathrm{cm}^2$ with a thickness of $320\,\mu$m are used. The choice of the pixel size (5×5 mm^2) has been guided by optimization studies with PFA.

R&D on the silicon wafers is still on going, to fully characterise the wafers (I-V and C-V curves, V_{bias}, depletion voltage), but also to solve issues seen with the physics prototype. A cross talk has been observed between the guard ring of the wafer and pixel at the edge of the wafer. This cross talk was visible by ‘square events’ in which all the pixel at the edge carried a signal. Studies have shown that segmented guard rings can reduce significantly this effect [7].

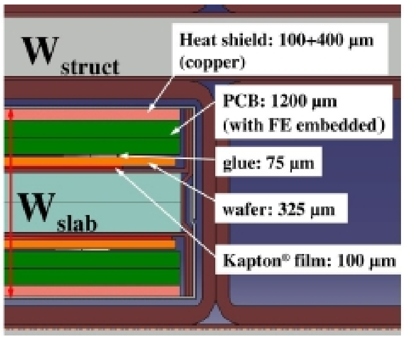

Figure 3: Cross section through one layer of the technological prototype.

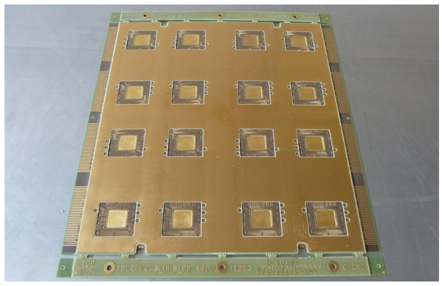

Figure 4: PCB prototype for embedding the chips.

4.2 The Active Sensors Unit

An Active Sensor Unit (ASU) is the entity composed of the read out ASIC, an interface card (PCB) and the silicon wafer. The SKIROC2 ASIC is designed to read out the silicon pin diodes of the Si-W ECAL [8]. It is a 64 channel ASIC with a dynamic range from 0.5 to ≈ 2500 MIPs, and an auto-triggering system at 50% of a MIP signal. The size of the ASIC is $7.2 \times 8.6\,\mathrm{mm}^2$. It will be power-pulsed in order to reduce the power consumption down to $25\,\mu$W/ch by taking advantage of the ILC spill structure.

The PCB carries the silicon wafer and the SKIROC2 ASIC, and has to fit inside the mechanical structure (see Fig. 3). This leads to constraints on the thickness (1.2 mm height) and the flatness (deviation from flatness max of 0.5 mm) of the PCB. To reach these goals PCBs with encapsulated unpackaged ASICs are the current design baseline (see Fig. 4). Less challenging alternatives, with packaged ASICs, are also under study. Temporarily, PCBs with packaged ASICs and relaxed constraints on the thickness have been used for the current test-beam. The silicon wafers are glued onto the back of the PCB using the conductive glue EPOTEK-4110. For the gluing robotic techniques similar to those described in [9] are under investigation.

5. Test beam Results

5.1 Experimental Setup

A first prototype have been tested with electron beam at the energy of 1 to 6 GeV, at DESY in spring and summer 2012. The prototype is equipped with 6 layers, each one with a $9 \times 9\,\mathrm{cm}^2$ silicon wafer reading out by 4 ASICs (see Fig. 5). The pixel size was 5×5 mm^2 giving in total 1536 channels working with the auto-trigger the SKIROC2 but without power-pulsing for this test beam. The layers are read out by a DAQ system [10]. The following results are obtained after a rejection of parasitic signals mainly due to a non-optimal power management of the ASICs.

5.2 Results

The goal of the test beam was to determine the signal over noise ratio of the detector and to establish a calibration procedure for all the channels. The signal over noise ratio is defined as the ratio between the distance pedestal - MIP and the sigma of the pedestal (see Fig. 6).

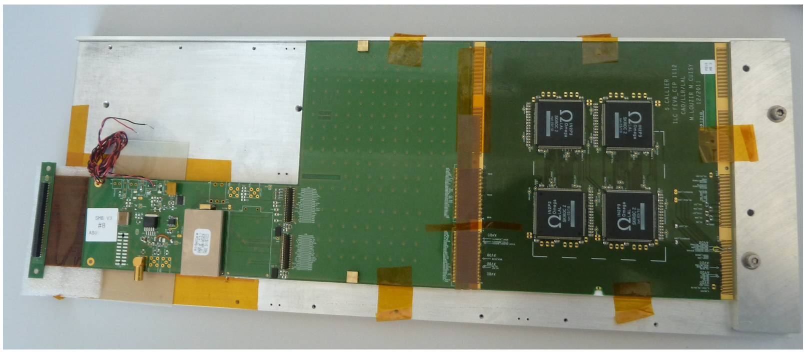

Figure 5: Picture of one layer of the Si-W ECAL setup tested in 2012.

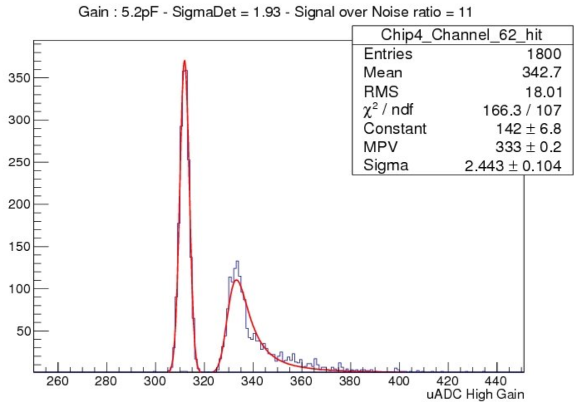

Figure 6: Pedestal and MIP distribution for one channel.

The signal over noise ratio is better than ten in all active cells in the 6 layers under study (see Fig. 7). Nevertheless there is a pattern on the distribution with the two chips on the right which have a lower signal over noise ratio. This is due to the fact that these ASICs have a larger pedestal width due to a longer electric line path in the PCB routing (see Fig. 8).

Next, the homogeneity of the detector response is analysed (x,y scan of the detector). After pedestal subtraction, the position of the MIP in one layer is around 73 ADC units $\pm$ 4 ADC units (see Fig. 9).

6. *R&D* Plans

The next *R&D* step will be to produce ASUs with four wafers readout by 16 ASICs. This step comprised the further studies of the PCB with respect to thickness and flatness. The deeper understanding of the SKIROC2 performance will result into a new development cycle of the ASIC (SKIROC3). The length of ECAL detector modules will be up to 2.5 m, so such a long layers are planned to be assembled and tested. Other test beams are also planned to use some layers of the prototype in power pulsing mode. Some power pulsed layers will be placed in a magnetic field in order to study the electrical and mechanical behavior.

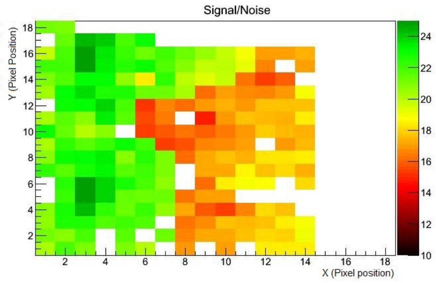

Figure 7: Map of the signal over noise ratio for one layer. The white spots are pixels linked to channels with disabled preamplifier, mainly due to details of the PCB rooting.

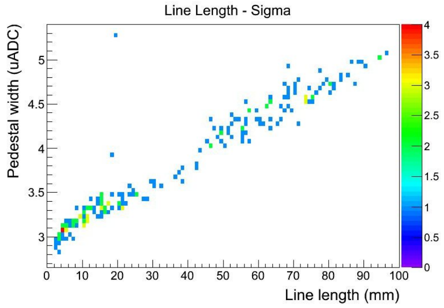

Figure 8: Dependence of the sigma of the pedestal as function of the electric line length on the PCB.

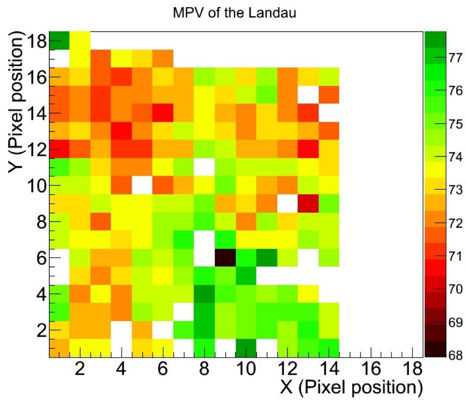

Figure 9: Map of the position of the MIP for one layer. The white spots are pixels linked to channels with disabled preamplifier, mainly due to details of the PCB rooting.

7. Conclusion

The particle flow algorithm requires highly granular calorimeters for detectors to be operated at a future linear electron positron collider. Therefore the *R&D* for a highly granular Si-W ECAL is on-going. After the proof of principle of the physics prototype, a technological prototype is constructed and tested, especially to study the engineering aspects of the project. A first test beam with idealized setup have been done at DESY in spring and summer 2012 and gives encouraging results with a signal over noise ratio better than for the physics prototype. Further *R&D* is now needed to test the power pulsing of the electronics, and the other real scale detector challenges.

Acknowledgments

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