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Construction and testing of a large scale prototype of a silicon tungsten electromagnetic calorimeter for a future lepton collider

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ABSTRACT

The CALICE collaboration is preparing large scale prototypes of 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 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 $9 \times 9\ cm^2$ silicon wafers. The front end electronics is integrated into the detector layers. The size of each pixel is $5 \times 5\ mm^2$. This prototype enters its construction phase.

We present results of the first layers of the technological prototype obtained during beam test campaigns in spring and summer 2012. According to these results the signal over noise ratio of the detector exceeds the *R&D* goal of 10:1.

1. Introduction

A linear electron–positron collider of up to at least 500 GeV should be the next major project of particle physics. 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 acceleration will be made by 16,000 superconducting radio-frequency accelerating cavities for the ILC whereas CLIC is based on a two-beam-acceleration concept. This next linear collider (LC) should be a complement to the LHC (Large Hadron Collider) of CERN. Indeed, unlike the LHC where the collisions are between protons, which are composite particles, the electrons and positrons are point-like particles. This has many advantages, as the knowledge of the initial state. In the case of the proton, the energy is shared between its different components. In the case of electrons the energy is concentrated in the point-like particles.

The scientific goal of the next LC will be to study in detail the new Higgs-like boson discovered at the LHC in July 2012. The LC will also permit to study the top quark, the dark matter and new physics beyond the standard model [1].

The physics goals of the LC require excellent jet energy resolution and particle identification in the multihadronic final state. Therefore, a new generation of detectors is developed for this accelerator. This good jet energy resolution is obtained by Particle Flow Algorithms (PFA) [2], which requires highly granular calorimeters.

The CALICE (Calorimetry for the Linear Collider Experiments) collaboration [3] is studying designs of highly granular calorimeters for the detectors of the next LC. The employed technologies are also useful for non-LC experiments (like PAMELA and PHENIX) and for applications beyond particles physics, like medical ones.

2. The particle flow algorithm

The CALICE calorimeters are optimized for the Particle Flow Algorithm (PFA). The idea of the PFA is to use the best suitable subdetectors to measure the properties of each of the particles of a jet. This means that the charged particles (65% of E_{jet}) will be measured using the trackers and not in the calorimeters. The two calorimeters, electromagnetic and hadronic, will be used to measure neutral particles. The photons (25% of E_{jet}) will be measured in the electromagnetic calorimeter, whereas the neutral hadrons (10% of E_{jet}) will be measured in the electromagnetic and hadronic calorimeters.

The PFA is already applied, by CMS for example, but with non-specific calorimeters, whereas the CALICE collaboration is working on calorimeters designed for the PFA. Indeed, in order to minimize confusion between charged and neutral particles in the calorimeters (leading to double counting/loss of energy) we need highly granular calorimeters.

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3. 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 together with the hadron calorimeter (HCAL) to measure the energy of showers from neutral hadrons. The precision physics at the LC requires that the calorimeters remain inside the magnetic coil. With its small Molière radius ($R_M = 9$ mm) and radiation length (X_0=3.5 mm) tungsten was chosen as absorber material. 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. Silicon pin diode matrices with a pixel size of 5×5 mm^2 are used as active material. For the ILD baseline the ECAL should be made of 30 layers, leading to 24 X_0 in total, equivalent to one interaction length.

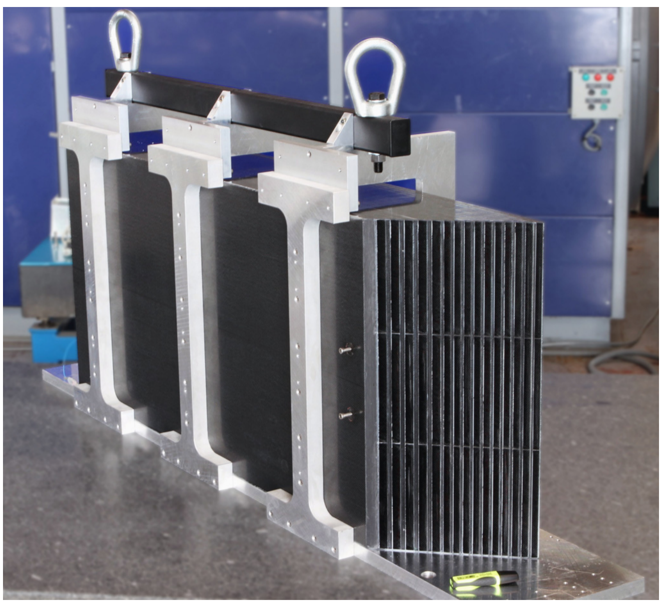

Fig. 1. Mechanical structure of the SiW-ECAL technological prototype.

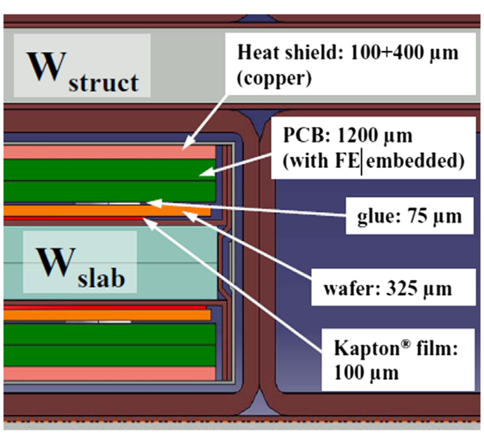

Fig. 2. Cross-section through one layer of the technological prototype.

4. The Si–W ECAL physics prototype

The physics prototype has been tested during 2003–2011 as a proof of principle for the Si–W ECAL [4]. The prototype was a compact and highly granular sampling calorimeter with tungsten as absorber and silicon as sensitive detector. 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. The active volume of the physics prototype consists of 30 layers with different tungsten thickness and, a silicon thickness of 525 μm, giving in total 9720 channels.

The physics prototype was tested in 2006–2011 in DESY, CERN and FNAL facilities with e^-, π, μ, 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 ($\sigma_E/E = 16.5/\sqrt{E}(\text{GeV}) + 1.1\%$) [5], but more important, it also shows good particles separation which is a major aspect for the PFA [6].

5. 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 has already been produced and tested with success (see Fig. 1). The front-end electronics will be integrated inside the detector layers (see Figs. 2 and 3) to keep compactness. A leak-less water system has been developed for the technological prototype and tested successfully at an earlier mechanical demonstrator.

5.1. The silicon wafers

The silicon wafers are the active material of the detector. In the prototype, Si wafers of 9×9 cm^2 with a thickness of 320 μm 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 characterize 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 in '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].

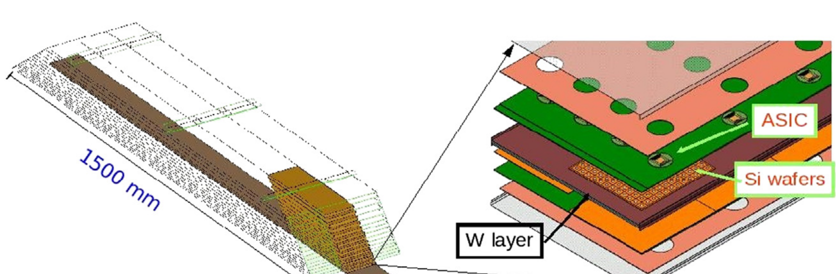

Fig. 3. Left: sketch of the layers inside the mechanical structure of the technological prototype. Right: exploded image of one layer.

5.2. 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 $7.2 \times 8.6\ \text{mm}^2$. It will be power-pulsed in order to reduce the power consumption down to 25 μW/channel by taking advantage of the ILC spill structure.

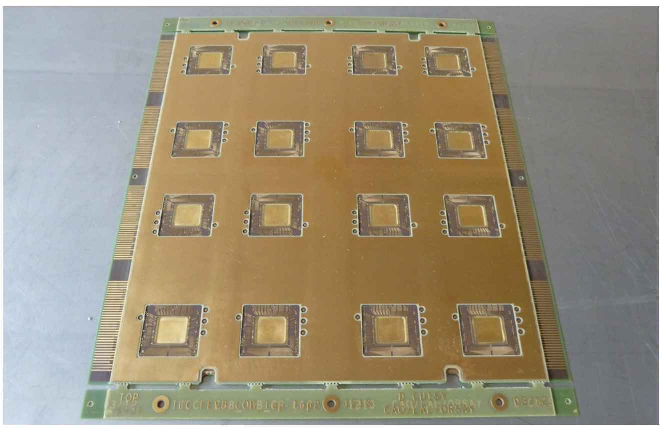

Fig. 4. PCB prototype for embedding the chips.

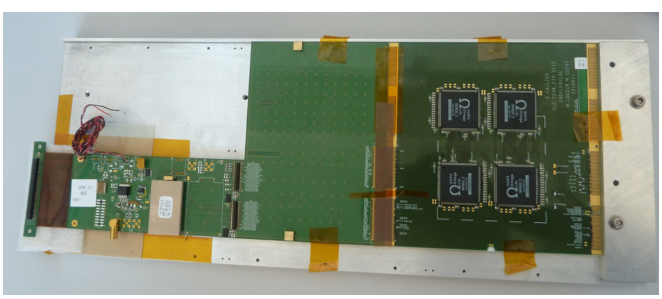

Fig. 5. Picture of one layer of the Si–W ECAL setup tested in 2012.

The PCB carries the silicon wafer and the SKIROC2 ASIC, and has to fit inside the mechanical structure (see Fig. 2). 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. Gluing robotic techniques similar to those described in Ref. [9] are under investigation.

6. Test beam results

6.1. Experimental setup

A first prototype has been tested with an electron beam with an energy of 1–6 GeV, at DESY in spring and summer 2012. The prototype is equipped with six layers, each one with a $9 \times 9\ \text{cm}^2$ silicon wafer read out by four ASICs (see Fig. 5). The pixel size was $5 \times 5\ \text{mm}^2$ giving in total 1536 channels working with the auto-trigger of 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.

6.2. 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).

The signal over noise ratio is better than 10 in all active cells in the six 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

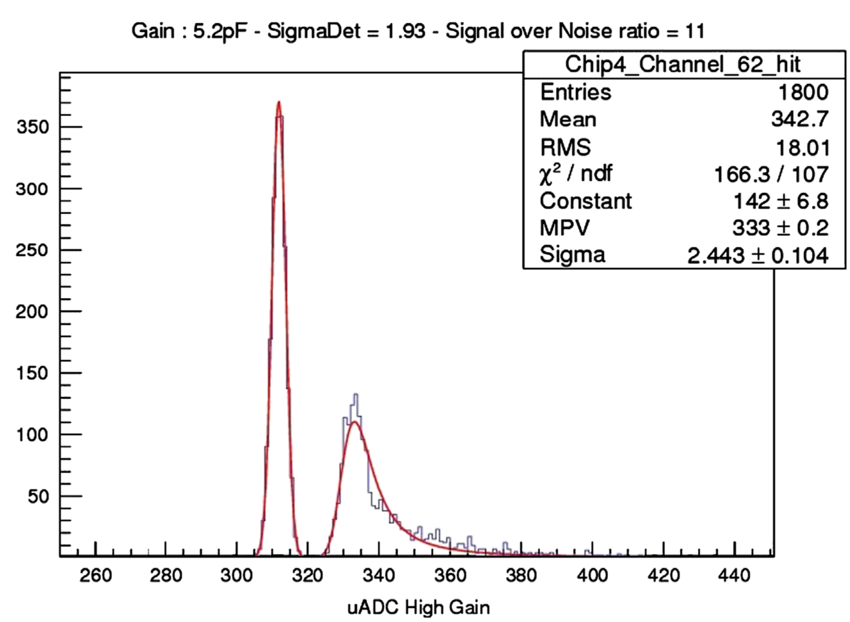

Fig. 6. Pedestal and MIP distribution for one channel.

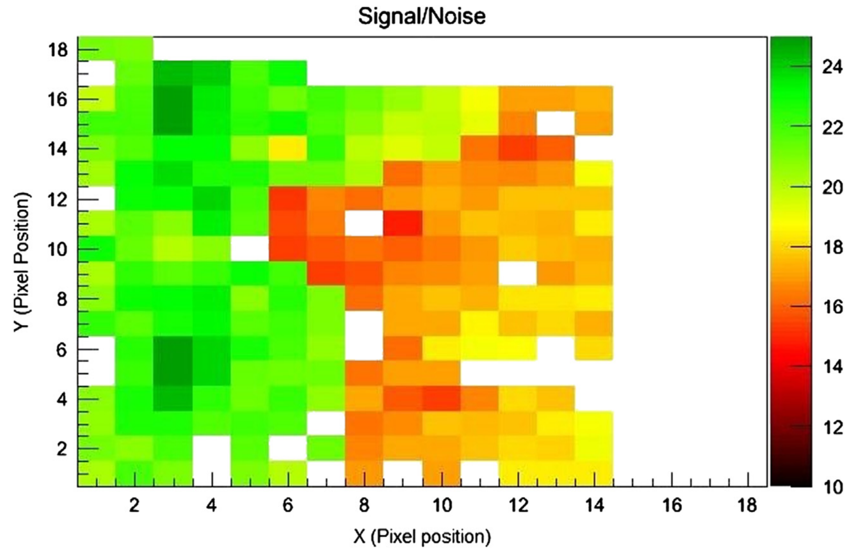

Fig. 7. Map of the signal over noise ratio for one layer. The white spots are switched off pixels, mainly due to details of the PCB routing.

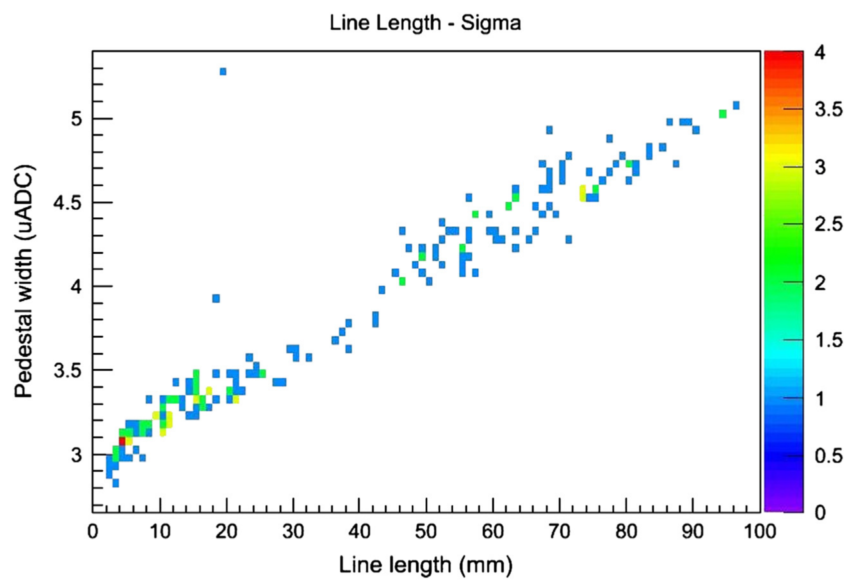

Fig. 8. Dependence of the sigma of the pedestal as function of the electric line length on the PCB.

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 analyzed (*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).

7. *R&D* plans

The next *R&D* step will be to produce ASUs with four wafers read out by 16 ASICs. This step comprises also 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 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.

8. 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 ongoing. 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 has 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.

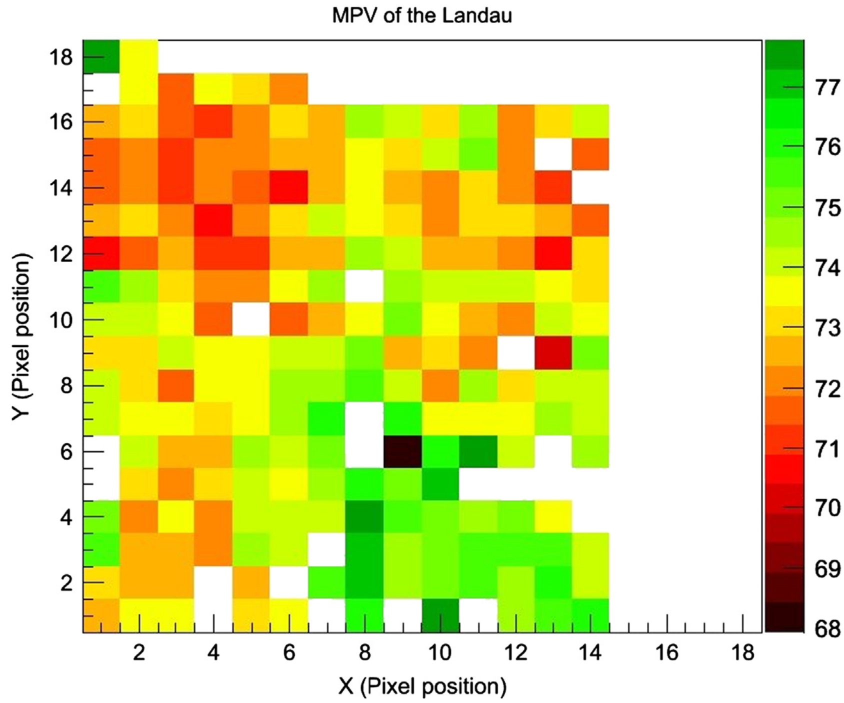

Fig. 9. Map of the position of the MIP pic for one layer. The white spots are switched off pixels, mainly due to details of the PCB routing.

Acknowledgments

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