EUDET-Memo-2009-13

Status of Silicon-Tungsten ECAL

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December 4, 2009

Abstract

The Silicon-Tugsten ECAL developed by the CALICE collaboration is a sampling calorimeter based on tungsten absorber and highly segmented (5×5mm) silicon sensor active layers. In this memo we describe the past achievements, present status and future plans of the project.

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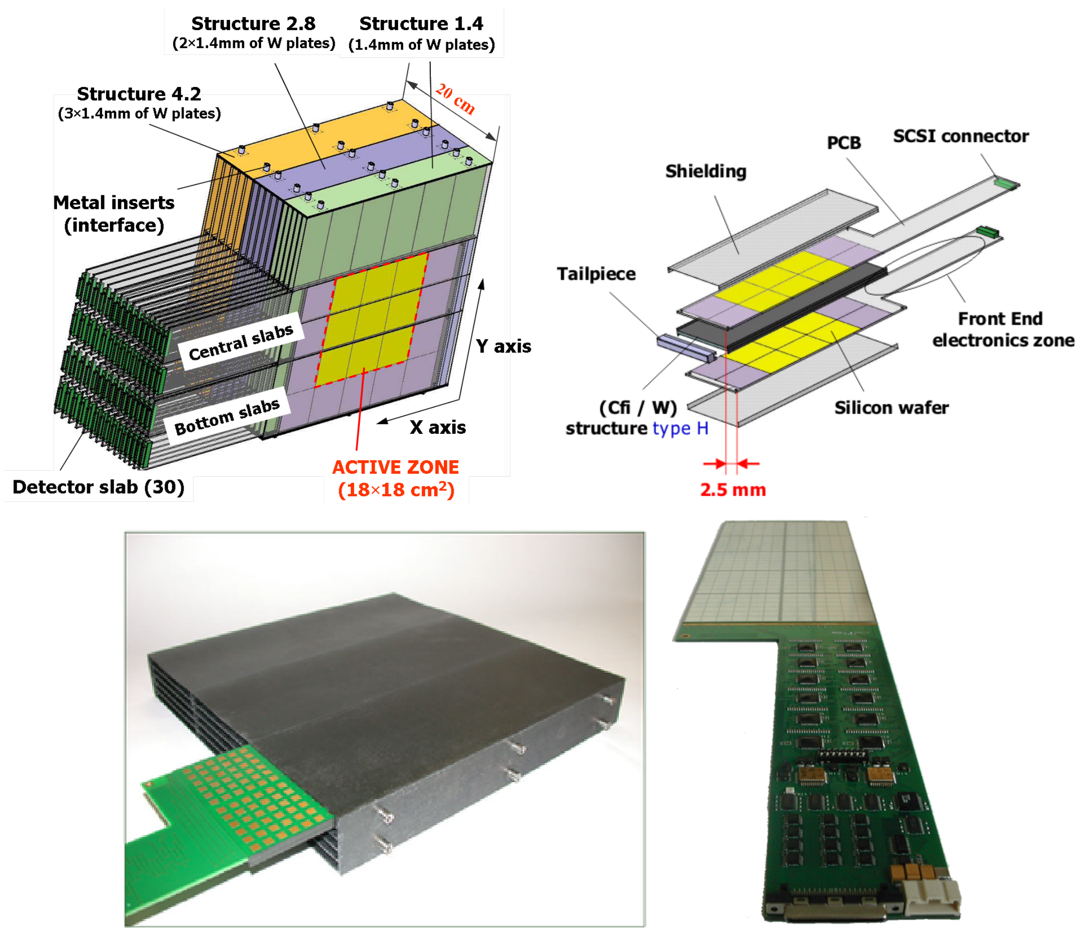

Figure 1: Cartoons (upper) and photos (lower) showing the alveolar support structure (left) and detector slab (right).

1 SiW ECAL

1.1 Physics prototype

A small detector prototype, the “physics prototype”, was developed to study the physics performance of a sampling electromagnetic calorimeter suitable for use in detector at a future Linear Collider. The detector was designed to satisfy the requirements of the Particle Flow approach to event reconstruction, in particular a compact size, small Molière radius, and high granularity. A 30–layer sampling calorimeter design was chosen, with three different sampling fractions, finer in the first layers and more coarse in the latter layers. Tungsten was used as absorber material due to its small Molière radius and large λ_I/X_0 ratio. The active layers were made of 300 μm thick silicon sensors, segmented into cells of $1 \times 1\text{cm}^2$, giving the high granularity required for the particle flow approach. It is described in [1].

These silicon detectors were mounted on printed circuit boards which channelled the signals to the front-end readout chip, mounted on the same PCB outside of the detector volume. Two PCBs were mounted on each side of an "H"-shaped detector slab which also incorporates a layer of Tungsten. These detector slabs were then inserted into an alveolar supporting structure composed of a carbon fibre-epoxy composite material, also incorporating half of the Tungsten absorber layers.

1.2 Operational experience with physics prototype

This ECAL prototype was exposed to test beams in 2006 and '07 (at CERN), and 2008 (at FNAL). Several hundred million events were collected in total, comprising a mix of calibration events and beam events with different particle pecies and momenta. Beams of electrons, positrons, muons, pions and protons were used at a range of momenta between 6 and 180 GeV/c. The detector ran stably over this three year operation period, in terms of calibration, energy response and linearity. No adverse ageing effects were observed.
In the next generation ECAL prototype (see below) the front end electronics will be placed inside the detector volume. A concern is that the electronics chips will produce spurious signals when they lie in the centre of a dense electromagnetic shower. To test this, a special detector slab was prepared, consisting of four readout chips, without any silicon wafers. This layer was placed into the physics prototype structure at the position of the E-M shower maximum, and exposed to high energy electrons. he analysis of the data indicate that the embedding of chips doesn't constitute a problem.

1.3 Detector performance

The collected electron data have been used to meausre the detector performance. Selecting events not significantly affected by dead zones of the detector, the detector response is seen to be linear in the energy range between 6 and 45 GeV to a level of around 1%, and the resolution of the energy measurement is measured to be $\sigma_E/E = 16.6/\sqrt{E} \oplus 1\%$. These results are well modelled in the Geant4 simulation of the detector. They are presented in detail in [2];
Further studies are underway to study the shape of electron showers, the position and angular resolution of the detector, fluctuations within electron showers, and the interaction of hadrons in the detector. The measurement of hadronic interactions will allow the tuning of the less well-understood modelling of hadronic interactions in the Geant4 simulation.
Several inconveniences were encountered in the operation of the detector. Some chips showed unstable pedestal values during the running period, requiring offline corrections to be applied to the data.
An serious problem was observed when an electron deposited energy in the guard ring (a structure at the edge of the silicon sensor which protects against high voltage breakdown). The deposited charge propagates around this structure, which, via the coupling between the guard ring and adjacent cells, produced events containing distinctive square shapes, with signals seen in all the cells at the sensor edge. This feature of the sensor has prompted R&D to improve it's design.

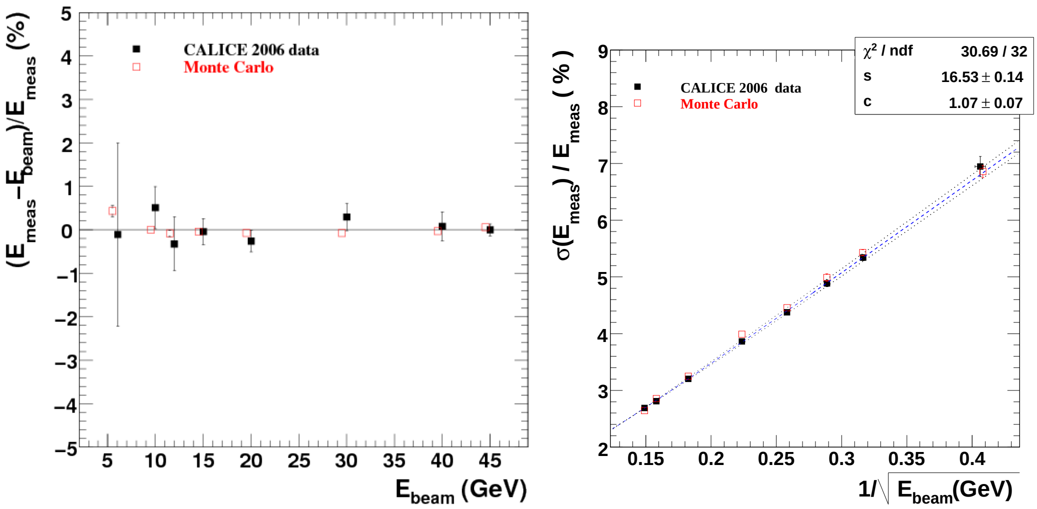

Figure 2: Graphs showing the measured SiW Ecal response linearity and energy resolution.

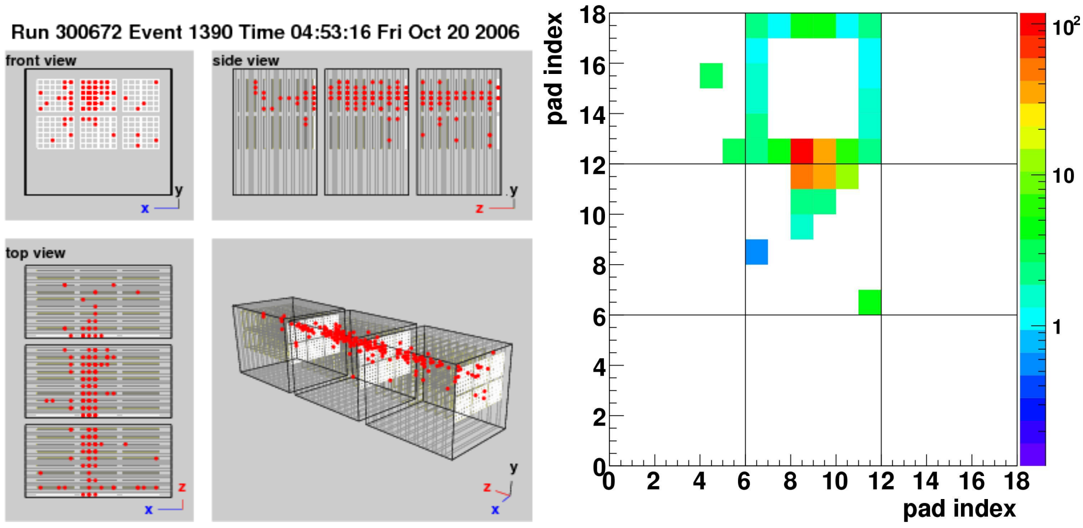

Figure 3: Event display of normal and “square” event.

1.4 Conceptual issues technical prototype, mechanics

The next stage towards the realisation of a final detector for a Linear Collider detector is the production of a technical prototype. This is conceived as a slightly smaller scale version of a single module of the final ECAL detector. It has the same shape as the ILD ECAL module design, the same number of layers, but somewhat smaller transverse dimensions. It is described in detail in [3].
To minimise the effect of dead areas at the edge of silicon sensors, larger $9 \times 9\text{cm}^2$ sensors have been developed. The design of the sensors' guard rings is under investigation to minimise the propagation of signals along the ring and the appearance of the so-called "square events". This next generation of silicon detectors will have a granularity four times higher than in the physics prototype, with a cell size of $5 \times 5\text{mm}^2$.
In contrast to the physics prototype, where the front end electronics was placed outside the detector volume, the technological prototype will have the electronics directly embedded in the PCBs which support the silicon detectors. This requires the design of ambitiosly thin and complex PCBs, and studies of the bonding and encapsulation of unpackaged chips.
The front end chip must consume very little power to prevent massive cooling requirements. They should in particular make use of the ILC bunch structure, where beam is delivered to the detectors only $\sim 1\%$ of the time. A power-pulsed design of the electronics will allow the chips to be powered for only the time when beam is delivered (plus some readout time), and will be powered down for the remaining $\sim 99\%$ of the time.
The zero-suppressed, digitised signals from the front-end electronics are then passed to the common CALICE DAQ system (see DAQ section).

1.5 Status and plans technical prototype

To study the fabrication of the Tungsten-composite mechanical alveolar structure, a intermediate step, a 3-layer "demonstrator" module has been constructed. This allowed the study of composite layer manufacture, cutting and finishing, as well as the assembly of the various layers into a final structure, together with tunsten plates and the thick composite back– and front–plates which provides the rigidity of the module. The manufacture of this module was a success, and the measured dimensions of the module satisfy the mechanical requirements. The ECAL will be fixed to the inner surface of the HCAL via a system of rails on the outer face of the ECAL modules. The demonstrator module incorporated such rails.
Work has recently started on the manufacture of the larger alveolar layers for the Technical Prototype. A first layer has been constructed using new moulds to reflect the larger size of the detector slabs for this prototype.
Research and development of the silicon sensors is in progress. Forty $9 \times 9\text{cm}^2$ wafers with $5 \times 5\text{mm}^2$ pixels have been supplied by Hamammatsu. A these sensors have been tested and show satisfactory electrical performance.
In the medium term, links will be forged with further industrial partners. This will introduce an element of competition to the sensor production, which should help to reduce

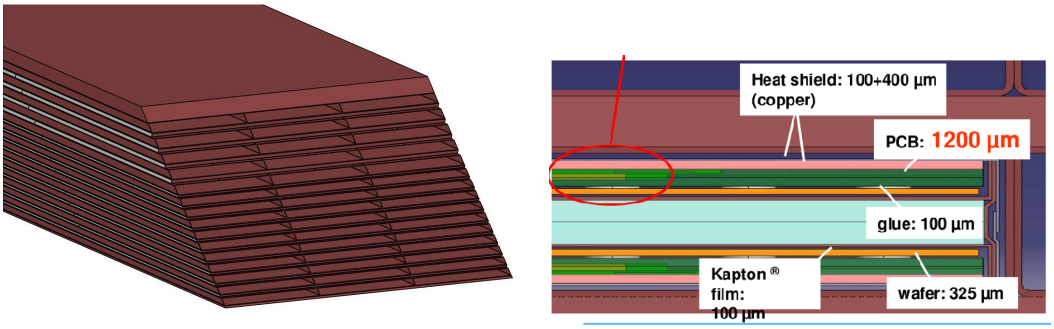

Figure 4: Design of Technological prototype. The left figure shows the mechanical structure, the right figure the design of the detector slab.

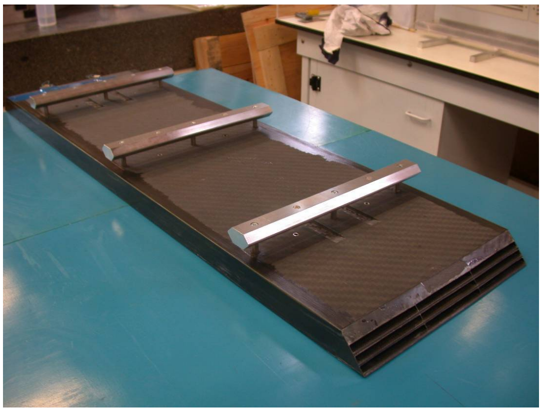

Figure 5: Photo of mechanical demonstrator module.

the sensor cost, which is at present prohibitively high when a complete ILC detector ECAL is considered. The EUDET ECAL module will be instrumented with sensors fom a number of different producers. A partnership with OnSemi and the Institute of Physics (Prague) is already underway as part of this process. An aspect of this collaboration is the study of the guard rings to minimise the occurance of “square events”. A number of small test sensors have been produced with different guard ring structures. Tests show that these designs do indeed reduce the propagation of signals around the wafer edge. A similar collaboration is developing with the Bhabha institute, who have also supplied a number of Silicon sensors which are undergoing testing.

The construction of the detector slabs is under study. A long string of up to ~ 10 “ASUs” (Active Sensor Unit, the PCB supporting the Si detectors) must be connected together. This connection is both mechanical and electrical - to supply power and send and receive data to the front-end chips. There are strong constraints on the available space for these connections, so a very thin, mechanically and electrically robust system is under design. A dedicated assembly bench has been produced, which allows safe and well controlled manipulation of the delicate ASU elements. Studies of ASU connection are underway.

The front-end chips are being designed. The EUDET module will be equipped with SKIROC2 chips. These are not yet available, in the meantime tests will be carried out using the SPIROC2 chip. This chip can be operated in a “SKIROC mode”, in which its behaviour is rather close to that envisaged for the SKIROC2 chip; however it has a smaller number of channels than the SKIROC2 chip, allowing only a subset of silicon cells to be read out. The operation of this chip in SKIROC mode has been tested on an electronics testbench, and shows the expected characteristics.

The design of the PCB is under study. The PCBs for the technological prototype will, in contrast to the PCBs used in the previous prototype, will hold the front-end chips inside the detector volume. The space available for the PCB is limited, to avoid degrading the detector performance; it must have a height of not larger than 1.2mm. This constraint places particular emphasis on the integration of the chips onto the PCBs and on how they are bonded. First samples of these boards have been received from two manufacturers, and are presently being evaluated.

A functional version of the board with relaxed erquirements on the thickness, has been manufactured, and is being tested. Further prototypes are being designed and submitted to manufacturers.

A cosmic testbench is under preparation, which will allow the whole chain of sensors, PCB, front-end electronics and DAQ system to be tested and debugged.

The removal of heat produced in the front-end electronics from the detector structure is essential for the integration of the ECAL into the general detector. At present a 400 micron sheet of copper extends along the length of the detector slab, acting as a thermal drain. The heat is extracted from this copper drain at the end of each module by a water-cooled system. Several possible designs for this system are under consideration, and a number of prototypes have been built.

Tests of this cooling system have recently taken place, consisting of a “fake” detector slab with heating elements inserted into the mechanical “demonstrator” structure, with

an attached cooling system. This test required an integration of the various detector elements: the PCBs, the "H" structure, ASU inter-connects, insertion into the mechanical structure, and attachment and running of the cooling system. No serious problems were found during the integration of these pieces. Recent tests of this cooling system showed an acceptably small difference in temperature between the ends of the detector slab under relatively high thermal load, and provided data which will be used to tune the thermal simulation of the EUDET detector module.
We plan to instrument a 18cm^2 tower of the next prototype (consisting of 30 layers) with sensors. One long detector slab will be prepared, to allow the testing of signal propagation along the entire ~ 1.5m length of a detector slab. The remainder will be composed of short detector slabs, each holding 2×2 silicon sensors per layer. The detector will be gradually instrumented as silicon wafers become available. A series of cosmic and beam tests will allow tests of the whole detector system, even with a partial complement of silicon elements. Combined tests with other detectors (HCAL, tracking, muon) are forseen as part of the CALICE programme.

References

[1] "Design and Electronics Commissioning of the Physics Prototype of a Si-W Electromagnetic Calorimeter for the International Linear Collider", JINST 3 (2008) P08001.

[2] "Response of the CALICE Si-W Electromagnetic Calorimeter Physics Prototype to Electrons", NIM A608 (2009) 372.

[3] "JRA3 Electromagnetic Calorimeter Technical Design Report", EUDET-Report-2009-01.