# 1 Calorimeter R&D

## 1.1 Silicon-Tungsten ECAL in ILD

### 1.1.1 Introduction

The group of the silicon-tungsten electromagnetic calorimeter for ILD aims to develop a highly granular detector optimized for particle flow measurements. The calorimeter uses a sandwich architecture of silicon sensors with $5\times5$ mm$^2$ pixels as active elements embedded in an alveolar structure made of tungsten and carbon fiber. The group is active in the development of simulation software and algorithms for calorimeter reconstruction, as well as in the design of readout chips, front-end electronics boards, mecanical structures, cooling and in ILD integration.

### 1.1.2 Recent Milestones

The work is now focusing on the construction of a technological prototype. This is a new milestone after the successful operation of the Physics Prototype in the years 2004-2011, including large scale beam tests at DESY, CERN and FNAL and data analysis [1].

In the technological prototype and in the ILD design the front end SKIROC chips [2] are embedded into the calorimeter layers and mounted on multi-layer printed circuit boards (PCBs). Four silicon sensors are glued with a conductive epoxy to the readout PCB. Depending on the ILD and the silicon sensor sizes, up to about ten of these PCBs will be connected together in-line and read out from one end by a data acquisition (DAQ) electronics. The sandwich of the silicon sensors with PCBs on both sides of the absorber layer represents one active module, called "slab". It is slided in the tungsten – carbon fiber alveolar structure. The slab absorber layer is also made of tungsten wrapped in carbon fiber. In this way, half of the absorber layers are in the structure and half are in the slabs.

A series of tests with simplified PCBs have been carried out starting from 2012: several beam tests at DESY, cosmic calibrations and infrared laser tests. Each simplified PCB served one silicon sensor. The power pulsing operation of the SKIROC chips has been demonstrated. The bias currents of the chips were shut down and raised with a frequency between 1 – 20 Hz. It was shown that the SKIROC currents should be switched on at least 600 $\mu$sec before physical events, so that all transition processes are finished. Mechanical rigidity of electrical interconnections under changing Lorentz force and also, the stability of pedestals was checked in the power pulsing mode in the magnetic fields of up to 2 T. The continuous cosmic data taking during 24 hours allowed to calibrate each pixel with 3% statistical accuracy. The variation of cosmic MIP signals across all channels was measured at 3-4% level. It was found to be dominated by the spread between the chips and by the variation of electronic channel gains within a chip. The same spread is measured by a calibrated charge injection into SKIROC preamplifiers. In cosmic and test beam data the signal-over-noise ratio for MIP signals was measured at the level of 8 – 20. It depended on the SKIROC gain, the better values were obtained for the gain 5 times higher than nominal.

The infrared laser tests have been used to study the so-called "square" events. They are caused by a capacitive coupling (cross-talk) between a silicon sensor guard ring and its boundary pixels. The guard ring ensures low dark currents of the sensor under high voltage. For technological reasons it is not grounded. High local signals at the sensor periphery may, therefore, propagate to all boundary pixels, fire them and produce "square" events. With an improved segmented guard ring design, the cross-talk is reduced to $\leq$0.5% per outer pixel side, as it was measured with the laser induced signals. Hamamatsu HPK company also developed a new "no guard ring" design, their small sensors demonstrated both the lowest guard ring cross-talks and

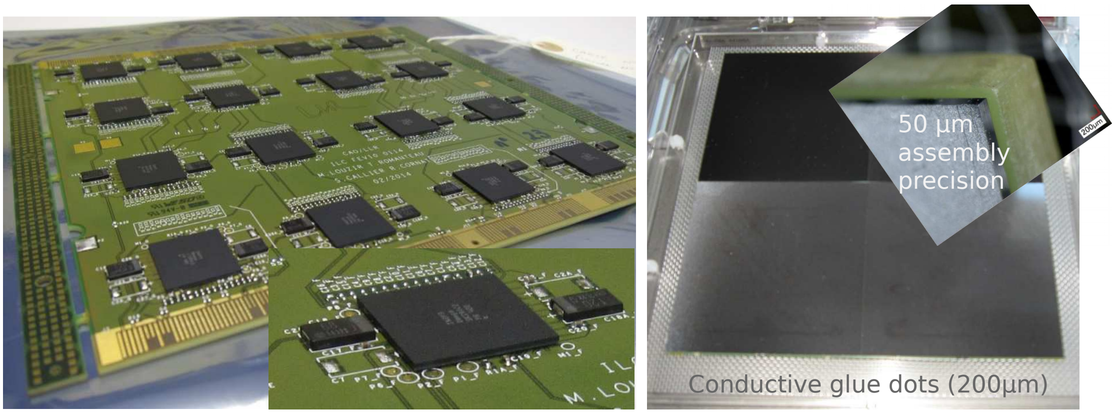


Figure 1: Left: new PCB with 16 SKIROC chips and 1024 channels, right: 4 sensors aligned and prepared for robotic gluing to PCB.

sufficiently low dark currents. Another activity which has been started in 2015, is the study of dark current dependence on neutron irradiation dose at a nuclear reactor.

Generally, the analysis of accumulated beam test, cosmic and infrared laser data validated the concept of the front end electronics. It will also allow for correcting an observed shortcomings of the SKIROC chips and the first PCB. A new version of PCB serving four sensors as required for ILD, has been designed and produced, see Fig. 1. To increase a channel density, a ball grid array (BGA) packaging of the SKIROC chips was chosen. The gluing of four fragile silicon sensors with a gap in between of only 100 $\mu$m has been successfully performed with a robot. The first detectors have been assembled in 2015 and the first tests with the cosmics and the laser have shown a good performance. An assembly procedure together with quality controls is formalized and well documented. Further improvement and production of the new version of SKIROC chips is planned for both ILD and for a CMS phase-2 endcap calorimeter upgrade project (HGCAL). The combined with HGCAL beam tests at SPS in CERN are planned in November 2015 and in 2016.

The mechanical design of ILD ECAL is well advanced. A full scale prototype of a barrel tungsten – carbon fiber alveolar module with three towers of 15 alveoli has been successfully produced with required tolerances. A full scale absorber part of the barrel slab has been also manufactured with tungsten substituted by carbon to reduce the cost. The mechanical simulations of one alveolus structure have been verified with the measurements using a special prototype with molded Bragg grating fibers. When elongated under loads, such fibers change a frequency of reflected light, allowing very precise measurements. The same technique is used in constructing buildings, bridges etc. A long 2.5 m endcap carbon structure with 3 alveoli is also successfully produced. The rails supporting ECAL on the HCAL face in ILD, and also the transport and handling tools for future ECAL assembly have been designed and mechanically simulated.

Thermal simulations have shown that a passive cooling inside alveoli should be sufficient. Outside water cooling will be performed with leakless loops, first prototypes exist.

In addition to the hardware development, there is a big activity on ILD optimization and on PFA algorithms. In particular, it was shown that the big ILD ECAL with fine longitudinal segmentation which was chosen in DBD on the basis of a physical performance, may be not optimal in terms of a cost effectiveness [3]. In particular, the number of ECAL layers may be reduced, eg. 19 layers provide only $\leq$10% worse jet energy resolution than the nominal 29. Even bigger cost savings may be achieved by reducing ECAL sizes. Eg. with an inner ECAL radius of

1400 mm instead of the nominal 1843 mm and a proportional reduction of an ECAL length, the 45–250 GeV jet energy resolution is degraded by 8–19%. It may be partially compensated by an increase in a magnetic field. In addition to the jet resolution, the performance of a smaller ILD for a reconstruction of tau decay modes has been studied [4]. It is essential for a measurement of CP-violation in $H^0 \to \tau^+\tau^-$ Higgs decays, where $\tau$ polarization is extracted from its decay products. It was shown, that the $\tau$ mode reconstruction efficiencies change by $\leq$1% when the ECAL radius is reduced to 1450 mm and the magnetic field is increased from 3.5 to 4 T. Based on these studies and taking into account the ECAL silicon sensor size, two new ILD models have been proposed for ILD community [5], with the ECAL inner radii of 1615 ("Khephren") and 1480 mm ("Mykerinos", by the name of the third ancient Egyptian pyramid). The ECAL engineering models for these sizes are under development.

Another important activity is a continuous improvement of PFA programs GARLIC [6] and ARBOR [7]. The former is specialized on a photon reconstruction in the highly granular ECAL, the latter is a PFA program approaching PANDORA [8] in performance. Both programs are under active development.

A shower fractal dimension measured in the highly granular calorimeter has been studied in [9]. It was demonstrated, in particular, that the fractal dimension could be effectively used to distinguish electromagnetic and hadronic showers. The performance of PANDORA, ARBOR and GARLIC to separate two electromagnetic or electromagnetic − hadronic showers is being verified with the physical prototype data collected in 2007 − 2011. Such a separation is crucial for reducing a PFA confusion. A good agreement between Monte Carlo and data has been observed. In another analysis, a detailed study of hadronic interactions recorded in ECAL physical prototype has been compared with GEANT4 models [10].

PANDORA jet energy resolution has been studied in DBD geometry [11] as a function of several ECAL parameters, including PCB thickness, guard ring size and fraction of dead channels and chips. It was demonstrated that the PCB thickness with BGA packaging already achieved in the technological prototype is sufficiently small (about $\sim$3% degradation of jet energy resolution compared to zero thickness). The standard guard ring thickness of 500 $\mu$m is also sufficiently small (1-2% degradation compared to zero). The dependence on the fraction of randomly distributed dead channels is rather weak, even at 10% the jet energy resolution degrades by $\leq$4%.

### 1.1.3 Plans for the near future

The ILD slab has on each side several PCBs connected in-line. Both supply voltages, clock and readout signals should be well propagated along the slab through the PCBs and interconnections between them. The assembly of in-line PCBs partially equipped with sensors (at least at the ends) is an important R&D activity for the future. For this purpose, we plan to develop an assembly line, incorporating the reception and the test of the material, the alignment of the PCBs, sensors and the interconnections, with a continuous monitoring for quality control purposes. First, a manual assembly line capable for a small production will be realized. Based on it, we will propose an automatized system for mass assembly together with industrial partners. A survey to search for such partners is a part of the proposal. A goal is to design the system such that it can be duplicated at other sites.

When built, the long slab will be tested at beams and with cosmics. The detailed characterization of channel responses will be obtained with the calibrated charge injection. A special study of various types of cross-talks is foreseen (across channels of one SKIROC chip, especially in high occupancy events, noise pick-up from PCB digital lines etc.).

Like this was done for the ECAL physical prototype, we plan common beams with other CALICE calorimeters, when our DAQ systems are sufficiently well integrated to acquire common data.

Hamamatsu HPK produces sensors from 6 inches wafers with the typical thicknesses in the range 300–500 $\mu$m. Another company, LFoundry in Europe, may produce in large scale the sensors from 8 inches wafers with the thickness of about 700 $\mu$m. Larger sensors have less fraction of guard ring dead area, while thicker sensors provide slightly better ECAL photon resolution. The LFoundry sensors which have been already ordered, will be tested in the future. In parallel, the tests of existing Hamamatsu prototypes will continue, in particular, the cross-talk studies with the infrared laser and the neutron irradiation measurements. The radiation hardness measurements of other slab components is also planned. The sensors from other companies (not only Hamamatsu) may also be tested in the same way. One may expect a future growth of a market of large area silicon detectors due to a future mass production of sensors for CMS HGCAL.

Other ECAL R&D may also greatly benefit from the synergy with the HGCAL project. It is expected that a new improved version of SKIROC chip will be manufactured for both HGCAL beam tests and for ILD. After that, when the SKIROC performance is proved to be sufficiently stable, a new chip generation will be designed and produced which will have zero (pedestal) suppression. Alternatively, if a new chip with superior characteristics will be developed for CMS HGCAL, it may be tested and adapted for ILD purposes (note, that HGCAL does not have the power pulsing and its bunch spacing is 25 nsec).

A continuous development of DAQ electronics is another important activity. In addition to the optimization of the baseline PCB with BGA packaging which should at least closely follow the SKIROC development, there is a R&D on embedding naked dye SKIROC chips inside the PCB. This option may provide $\sim$1.5 mm thinner active ECAL layer, but is technologically challenging because of the constraints on the required PCB flatness. Further R&D on improvement and miniaturization of DAQ electronics placed at the end of the slab, and also, on low and high voltage distribution systems is also foreseen.

All activities mentioned above also imply the search for industrial partners where the future mass production may be realized. This also means a continuous work on a cost estimation and optimization of all ECAL elements.

The work on physics – cost optimization of ILD ECAL will continue, together with the optimization of PFA algorithms. ECAL endcap ring should be designed taking into account high backgrounds closer to the beam pipe. The questions of ECAL integration in ILD, its assembly and safety will be further elaborated.

### 1.1.4 Engineering Challenges

The following challenges will have to be addressed when proposing this technology for ILD:

- cost reduction of calorimetric silicon sensors, direct contact with producers is already established (Hamamatsu, LFoundry, On-Semi, ...).
- A chip with the good trigger stability, dynamic range, low noise and power dissipation, power pulsing etc.
- Integration in a compact device, satisfying all the requirements (mechanical tolerances, readout signal quality, heat dissipation / cooling, reliability).
- Industrialization of solutions, scalability of all elements for O(10M) or 100M channel detector.

### 1.1.5 Applications Outside of Linear Colliders

- CMS phase-2 upgrade project of the endcap calorimetry (HGCAL).
- The compact Silicon-W design has been used in the PAMELA satellite (very similar to the CALICE SiW ECAL physics prototype) [12].
- Future circular $e^+e^-$ high energy colliders (FCC in CERN, CEPC in China) may also use this technology.

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