Available online at www.sciencedirect.com
ScienceDirect
Nuclear and Particle Physics Proceedings 273–275 (2016) 2554–2556
www.elsevier.com/locate/nppp

Development of a Highly Granular Silicon-Tungsten ECAL for the ILD

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Abstract

The excellent jet energy resolution required for precise physics measurements at ILC is achievable using a Particle Flow Method and highly granular calorimeters. As it was shown by CALICE international R&D collaboration, the silicon-tungsten imaging electromagnetic calorimeter provides the best granularity, stability and resolution of jet energy measurement. After proving the calorimeter concept with physical prototypes in 2005-2011, an emphasis is now moved to building a technological prototype satisfying challenging requirements. All chosen technologies should be reliable and scalable for a mass production of a future detector. We report on the current status of R&D, in particular, on beam and charge injection tests of the technological prototype and on the tests of ECAL mechanical structure. We also report on our plans to build a realistic prototype detector and test it together with an existing carbon fiber-tungsten mechanical structure. A similar silicon-tungsten calorimeter technology has been recently proposed for the Phase 2 upgrade of CMS end-cap calorimeter and future high energy circular collider projects.

Keywords:
Silicon Detector, ECAL, Calorimeter, ILC

1. Introduction

International Linear Collider (ILC) is e^+ e^- linear collider at 250-500 GeV center-of-mass energy, the energy is extendable to 1 TeV. Higgs boson whose mass is around 125 GeV was discovered by ATLAS and CMS experiments at LHC. Higgs boson becomes a new probe to explore physics beyond the standard model. The ILC has capability of very precise measurement of the higgs boson and other standard model particles under clean experimental environment.

The ILC detector concept is based on excellent resolution of jet energy measurement with Particle Flow method to realize the precise measurement. Particle Flow Algorithm (PFA) is developed to archive high resolution of jet energy which can separate Z and W boson mass reconstructed with two jets. The PFA requires precise 3-D position resolution to vertex detectors and trackers and calorimeters to separate each particles in a jet. We Silicon tungsten electromagnetic calorimeter (Si-W ECAL) R&D group choose a pixellized silicon sensor technology to maximize the PFA performance with high granular calorimeter.

For operating the ILC detectors, Power Pulsing (PP) technique is essential to reduce power consumption and heat generation. The idea of PP is that a part of detector power is shut down or reduce as much as possible between ILC bunch train. The Si-W ECAL must be operated with PP technique.

2. Si-W ECAL

The Si-W ECAL is one of ECAL candidates of International Large Detector (ILD) for ILC. The Si-W ECAL is a sampling calorimeter consisting of 20-30 silicon active layers and pure tungsten absorbers. We can make compact ECAL and small jet radius by using tungsten absorber. The silicon sensor with 5×5 mm^2 cell size is

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.457

optimized the jet energy resolution with PFA with respect to cost of ECAL.

2.1. Physics Prototype

The physics prototype of the Si-W ECAL was constructed and tested as proof of principle detector with high energy particle beam from 2005 to 2011. The phys. proto. consists of 30 layers of 18×18 cm^2 active area and tungsten absorbers and silicon sensor with 36 cells/sensor, cell size is 1×1 cm^2, and 9720 channels and external readout electronics. The definition of energy resolution is

$$\frac{\sigma_E}{E} = \frac{\sigma_{\text{stochastic}}}{\sqrt{E(\text{GeV})}} \oplus \sigma_{\text{constant}}. \quad (1)$$

The phys. proto. archived the energy resolution to electron ranging 6-45 GeV of $\sigma_E/E = 16.53 \pm 0.14(\text{stat.}) \pm 0.4(\text{syst.}) \oplus 1.07 \pm 0.07(\text{stat.}) \pm 0.1(\text{syst.})$. The result satisfies requirement to ILD ECAL performance for single electron. The first results of phys. proto. are published in these articles [1, 2, 3, 4].

2.2. Technological Prototype

Since 2010, we have developed Si-W ECAL technological prototype to investigate and solve technological challenges toward the full-size ILD Si-W ECAL. The tech. proto. has fully embedded readout electronics. SKIROC2 ASIC[5] is developed for the electronics and has almost all the functions which are required to final detector. SKIROC2 equips variable gain charge amplifier and 12-bit ADC and digital logic and some digital/analog couplings and power pulsing with a 1 % duty cycle and self-triggering capability. The Si sensor has 324 channels of 5 × 5 mm^2 cell in 9×9 cm^2 area. We produced 14 short slabs as proof of feasibility and performed 4 test beams.

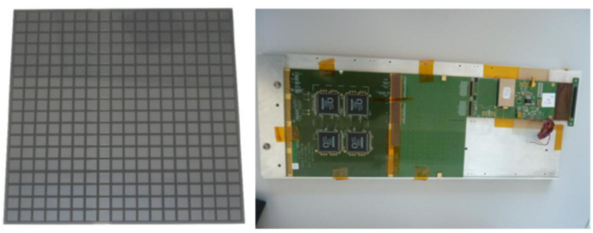

Figure 1: Left: Si sensor with 324 channels. Right: A slab of technological prototype.

In 2012, first and second test beams of the tech. proto were successfully performed aiming to operate embedded Front-End (FE) electronics with non PP condition at DESY. The tech. proto. archived excellent MIP signal to noise ratio above 10:1 shown in Fig. 2 left. To deeply understand the tech. proto. our detector is implemented into precise GEANT4 simulation. In Fig. 2 right, simulation and data are in good agreement with careful treatment at digitization phase. Details of ASIC study is described in the article[6].

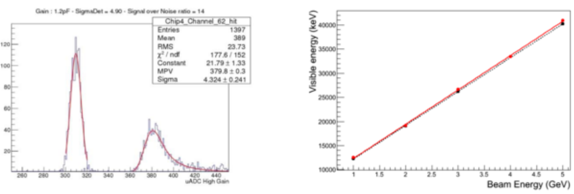

Figure 2: Left: pedestal and MIP response. Right: comparison of data with GEANT4 simulation.

In 2013, we successfully operated the tech. proto. under PP condition. For ASICs connected with short lines we could operate in PP and in Continuous Current (CC) mode. The others showed a degraded performance in CC and PP mode. We measured MIP events in both PP and CC mode with positron beam at DESY. We measured ramp-up time of FE electronics in PP operation. It takes about 600 μs until the detector is operational after the ramping up of the bias currents. We measured ohmic resistance across the interconnection between two Active Sensor Units (ASUs) with various duty cycles and frequencies. This study is also important to operate long slab, because ILD calorimeters will be placed inside of solenoid magnet. The ohmic resistance is insensitive to magnetic field up to 2 T and varies about 20 mΩ by thermal effect.

3. Silicon Sensor Study

We proceed R&D of silicon sensor itself cooperating with Hamamatsu Photonics (HPK). Initial R&D on split guard-ring[7] has been made together with ONsemiconductor in 2008 and continued with HPK. We tested four types of small sensors whose cell size is 5.5 mm^2 with different guard-ring design manufactured by HPK. The guard-ring types are no guard-ring and one guard-ring and two and four split guard-rings. We also tested different resistivity samples which are produced in 2012 and 2013, the resistivity of 2013 model is higher than 2012 model. We measured leakage current and capacitance of Si sensors for each guard-ring type and two different resistivity samples. guard-ring design do not much affect the leakage current and capacitance ranging 0 to 300 V of bias voltage. On the other hand, high resistivity Si sensor has lower leakage current and full depletion voltage than the other Si sensor. Higher resistivity Si sensor is more suitable for Si-W ECAL.

At the test beam of phys. proto., we observed a crosstalk along a guard-ring. We measured Si sensor response with IR laser whose wavelength is 1064 nm. The IR laser can uniformly make electron-hole pair in Si sensor, hence we can make similar situation of high energy charged particle beam in the laboratory. We could reproduce crosstalk along guard-ring with one guard-ring sensor. On the other hand, no guard-ring and two and four split guard-ring samples did no make crosstalk. Irradiation test is necessary to decide the final design of guard-ring but no guard-ring Si sensor shows promising results.

4. Next Steps Toward the Real Calorimeter System

We are proceeding R&D to prove feasibility of full size calorimeter system. There are many studies such as calorimeter structure, cooling system, PCB design, method of gluing PCB and Si sensor, ASIC development, Si sensor design, DAQ system and anything related to calorimeter system. The Si-W ECAL will be supported by carbon fiber-tungsten mechanical structure and a structure prototype was produced and tested. We study two PCB designs which are BGA packaged chips and PCB with naked die. We are developing large size PCB which can carry four wafers and 16 ASICs. Development of long layers consisting of 10 ASUs are ongoing. We are testing electronic contact of a long slab without Si sensor (Fig. 3). We plan to produce 1 or more long and short slabs to fill an existing tower in full scale mechanical prototype and perform system test with next PCB versions. ASIC development is also ongoing and next ASIC version (SKIROC2b) will be available soon.

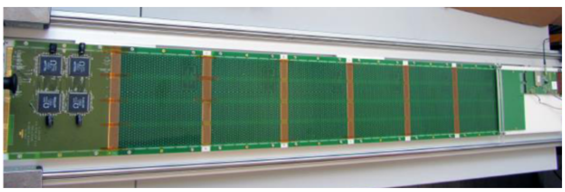

Figure 3: long slab using 1 ASU with 6 passive extender boards.

5. Deployment of Si-W Calorimeter

We are developing and proving feasibility of Si-W ECAL for ILD and the ideas and techniques are deployed other experiment. The CMS experiment is investigating installing a silicon-based high-granularity calorimeter (HGC) shown in Fig. 4 right, when the LHC is upgraded in 2023. Ideas, engineering, simulations and test beam results have been critical in the design of the detector for CMS. Main differences comparing with the ILC environment are as follows.

- High radiation - maximum 10^{16} neutron/cm^2
- Temperature - Operate at -30 °C
- Power - Continuous operation (100 kW)
- Cooling - Bi-phase CO_2

Silicon thickness is thinner, 100-200 μm wafer, to limit heat load due to unavoidable radiation damage. HGC CMS is using PandoraPFA to reconstruct electrons, hadrons and jets in the calorimeter. Mechanics is similar but not identical ILD's design. CALICE test beam results are the benchmark for validating Monte Carlo results.

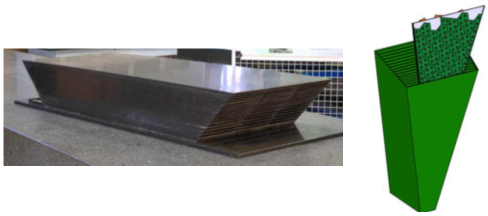

Figure 4: Left: ILD ECAL structure design. Right: HGC CMS design.

Acknowledgments

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025, the French ANR program, the French IN2P3 Quarks and Leptons program and the JSPS KAKENHI Grant Number 23000002 and the MEXT KAKENHI Grant Number 23104007. We would like to thank the CERN and DESY test beam facility team for their support. We would like to thank the CALICE collaboration for productive discussions.

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