PROCEEDINGS of
CHEF 2013

The silicon-tungsten electromagnetic calorimeter for ILD

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The electromagnetic calorimeter for the International Large Detector concept has been designed with the requirements of Particle Flow reconstruction as guiding principles. The main requirement is for highly efficient particle separation, leading to a design with high readout granularity. On option for the electromagnetic calorimeter, described in this paper, is a sampling calorimeter with tungsten absorber and detection based on silicon PIN diodes.

Calorimetry for High Energy Frontiers - CHEF 2013,
April 22-25, 2013
Paris, France

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1. Introduction

A future high energy lepton collider [1, 2] will have the capability to make high precision measurements of the Higgs, top and electro-weak sectors, as well as possible physics beyond the standard model. To make full use of the collisions produced by such a collider, a detector which can measure the produced final states with excellent precision should be built. In the case of the International Linear Collider (ILC), a proposed electron-positron collider operating at centre-of-mass energies of up to 1 TeV, two detector concepts are being studied, ILD and SiD [3].

These detector concepts are both being designed to allow the optimal use of Particle Flow reconstruction [4], an approach to event reconstruction which emphasises the measurement of each final state particle produced in an event. Such an approach gives substantial improvements in the energy measurement of hadronic jets over past and present detectors.

In this paper we discuss the requirements and design of the silicon-tungsten (Si-W) electromagnetic calorimeter (ECAL) designed for the ILD, emphasising its role in the reconstruction of hadronic final states and the implications this has on its design. We also discuss the results of several studies aiming to optimise the design of such an ECAL.

2. Role of ECAL in ILD

The ILD concept is designed around Particle Flow reconstruction. This technique implies the measurement of each particle produced in an event. This is different to past and current general purpose detectors, most notably in the design of the calorimeters, which traditionally measure the sum of energy deposited by a number of particles. In contrast, calorimeters optimised for PFA must individually measure the energy of each particle, implying a very fine readout granularity. The advantage of such a technique is that it allows a choice of which sub-detector to use to measure a given particle's energy: the optimal choice is to use the most precise sub-detector measuring a particular particle. In practice, this means using the magnetic spectrometer/tracker system to estimate the momentum of charged particles (on average $\sim 65\%$ of a jet's energy), the electromagnetic calorimeter for photons (25% on average), and the hadronic calorimeter (HCAL) of neutral hadrons ($\sim 10\%$). In this way, the high precision tracker is used to measure the majority of a jet's energy, while the less precise calorimeters are used to estimate only a minor fraction of the event energy. The main limitation to PFA performance, particularly at higher jet energies, is the confusion between calorimeter energy deposits from charged and neutral particles, which can lead to an over- or under-estimation of energy, degrading the jet energy resolution.

The main roles of the ECAL are therefore to allow the separation of calorimeter deposits from nearby particle showers, allowing each particle to be measured individually, and the estimation of the energy of electromagnetically interacting particles, mostly photons, which arrive at the ECAL.

3. ECAL design

These roles have several implications on the ECAL design. The pattern recognition requirement, which requires the ability to cleanly separate the energy deposits in the calorimeter due to nearby particles, leads to an ECAL with a very fine readout granularity to accurately resolve nearby particle showers. An ECAL at a large distance from the interaction point, and a strong magnetic field, help to increase the typical distance between particles at the ECAL, and therefore to improve the performance of event reconstruction. A small Molière radius constrains the transverse size of EM showers, helping to cleanly separate nearby particle deposits. An ECAL with a hadronic interaction length significantly longer than its radiation length (X_0) will allow the longitudinal profile of particle showers to be more effective in separating nearby photons and hadrons.

The ECAL must be able to measure photons with energies between $\sim$ 500 MeV to 250 GeV, the highest energy photons which can be produced at a 500 GeV centre-of-mass energy collider. A total thickness corresponding to 24 X_0 ensures that most energy from electromagnetic showers is contained in the ECAL. The energy resolution required for Particle Flow-based reconstruction of hadronic jets is not particularly stringent: a single photon energy resolution with a stochastic term of 15% gives a rather small contribution to the total jet energy resolution [5].

From the point of view of the integration of the ECAL into a complete detector, several points should be considered. The amount of material in front of the calorimeter must be minimised as much as possible. Particularly damaging to Particle Flow performance are hadronic interactions occurring in the inner tracker region, which can lead to an increase in the confusion term. Due to this necessity to minimise the material in front of the ECAL, both it and the HCAL are placed inside the solenoid which provides the magnetic field. To limit the size and cost of this solenoid, the geometric thickness of the calorimeter should not be too large. Since the density of readout channels is very high due to the needs of pattern recognition, is is important to minimise the number of readout cables passing out of the detector, which could represent very substantial dead volumes inside the detector. For this reason, highly integrated electronic readout systems have been designed which can be situated within the volume of the ECAL. For the same reason of high channel density, the power consumption of these integrated electronics must be as very low in order to minimise the cooling needs, and the dead materials which a substantial cooling system would entail.

For an ECAL of the scale being considered for ILD, a highly industrialised production process will be required. An ECAL design which is highly modular, and allows quality control testing at many stages during the construction, is therefore essential if the final detector is to be realised in a reasonable time, budget, and with high reliability. Access to the ECAL will be extremely time-consuming after detector construction, and should be avoided as much as possible. This factor again emphasises the need for extensive quality control at several stages during manufacture and assembly.

4. Silicon-tungsten ECAL

The silicon-tungsten ECAL being developed for ILD is based on a sandwich sampling calorimeter design with tungsten absorber and silicon PIN diodes as the active medium. More details on the technical realisation and testing of such an ECAL by the CALICE collaboration are presented in [6].

Tungsten is a suitable absorber material due to its short radiation length of 3.5 mm, relatively long pion interaction length of 11.3 cm, small Molière radius of 9 mm and good mechanical properties, suitable for producing large, self-supporting structures. The silicon PIN diodes (used in fully-depleted mode) have a very stable response with respect to variations in temperature and volt-

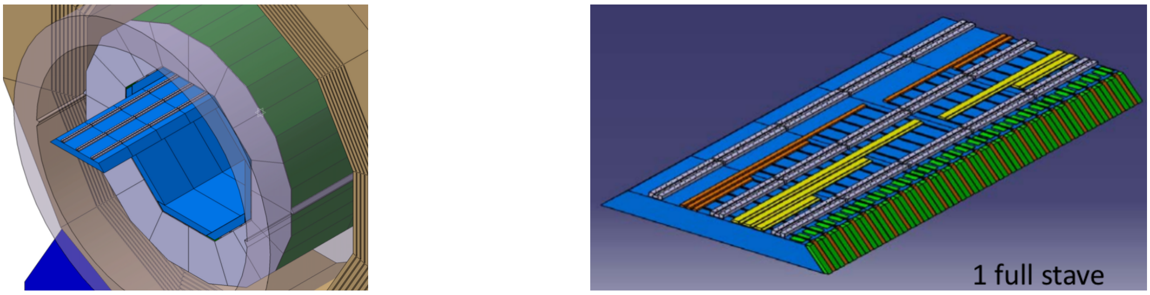

Figure 1: The ECAL of ILD. Left: the last ECAL barrel stave being slid into the ILD. Right: detail of one equipped barrel stave. The carbon-fibre structure is shown in blue, the cooling system in brown, electronics cards in green, and cables in yellow. The three rails are shown in grey.

age, and present no intrinsic limitations of dynamic range. The sensors are very thin ($\sim 330\mu$m), allowing a compact calorimeter with small effective Molière radius to be built. The default Si-W ECAL design has thirty sampling layers (and 29 absorber layers). The sampling structure of the ECAL has two sections in depth: the first twenty tungsten layers have a thickness of 2.1 mm (60% of a radiation length), while the last nine absorber layers are two times as thick. This gives a good energy resolution and detection efficiency for lower energy photons, while limiting the total number of sensitive layers and therefore also the cost.

4.1 Mechanical design

The overall form of the ECAL is that of an octagonal tube with an inner radius of 1843 mm and a half-length of 2350 mm, closed by two endcaps. The tracking system, consisting of a large TPC and a number of silicon tracking layers, sits within this ECAL tube, which is in turn surrounded by the HCAL. The ECAL barrel is made up of eight "staves" in the azimuthal direction, each in turn made of five modules along the beam direction. This gives a total of forty identical modules in the barrel. These modules have a trapezoidal cross-section with a maximum dimension of 1.5 m, and a height of around 0.2 m. The length of the module (along the beam (z) direction) is around 0.9 m. The module is an alveolar structure made of a carbon-fibre composite, incorporating half of the tungsten absorber layers. Five columns of alveoli are placed along z, each consisting of fifteen alveoli in the radial direction. The width of each alveolus is 182 mm, with a height of $\sim 7(9)$ mm for the inner ten (outer five) alveoli. Detector slabs are inserted into these alveoli. Each endcap is divided into four identical quadrants, which each consist of three alveolar modules with a longer length (up to 2.5 m), but otherwise similar structure to those in the barrel. The use of a carbon-fibre composite material allows the thickness of internal walls between alveoli to be only around 1 mm, with an additional 1 mm thickness in the external module walls. Thicker carbon-fibre plates are incorporated into the inner and outer faces of the modules to provide structural stiffness and an attachment system to the inner HCAL face based on a system of rails. The sensitive detectors are mounted on so-called H structures, based on a tungsten layer wrapped in carbon fibre, which are slid into each alveolus.

4.2 Silicon sensors

The sensors for the active layers are made from ~ 330 μm-thick 6" wafers of high resistivity silicon. These are processed to make an 16×16 array of square pixels in an area of 9×9 cm^2. A guard ring structure around the edge of the sensor prevents surface leakage currents. A number of different sensor designs have been prototyped and tested. Parameters which have been studied include the resistivity of the raw wafers used, various different guard ring designs, different wafer cutting techniques, and different widths of the margin between the guard ring and the sensor edge.

4.3 Sensitive layers

The sensitive layers are built of a number of modules called Active Sensor Units (ASUs). Each ASU is built around an 18×18 cm^2 printed circuit board (PCB). One side of the PCB is equipped with 32×32 pads, to which the pixels of four silicon sensors are glued using a conductive epoxy (EPO-TEK 4110). The other side of the PCB houses sixteen SKIROC ASICs which treat the signals from the silicon sensors. The PCB contains connections between the sensors and ASICs, the power and readout lines for the ASICs, as well as several ground layers to shield the analogue signals from the digital lines.

The SKIROC2 ASIC currently being used is a 64-channel chip, each channel of which provides a variable gain pre-amplifier, a fast shaper for triggering purposes, and two slow shapers with different gains for charge measurement. The analogue charge is stored in a 15-deep memory, and then digitised by a 12-bit Wilkinson ADC. The ASIC has been designed to run in power-pulsed mode, which limits the average power consumption to around 25 μW per channel.

A string of such ASUs is assembled by bonding several ASUs together. A technique based on soldered Kapton connectors has proved very successful. The bias voltage for the silicon sensors is provided by a single large Kapton sheet per ASU string, glued to the silicon sensors. The final element in a string of ASUs is the Detector Interface Card (DIF), which controls the communication to the ASICs and the data acquisition.

One string of ASUs is mounted on each side of the mechanical “H” structure, with the side hosting the silicon sensors towards the centre. A sheet of copper, around 0.4 mm thick, is used to cover each side of the slab. This sheet helps evacuate heat produced in the ASICs to the end of the slab where the cooling system is attached.

4.4 Detector integration

All data sent to and from the ASICs are sent via the DIF cards, one of which is attached at the end of each string of ASUs. The data from the DIFs are multiplexed by the Local Data Aggregator (LDA) cards (or alternatively, the Data Concentrator Cards (DCC)). Timing synchronisation is handled by the Clock and Control Cards (CCC). These various cards are to be placed in the 3 cm gap between the ECAL and HCAL, along with the ECAL power and readout cables, and the cooling system services.

4.5 Cooling

Within the detector volume, power is dissipated in the ASICs and in the components of the DAQ system. A leak-less water-based cooling system has been designed to extract this heat from the detector. A heat exchanger, in which water at sub-atmospheric pressure circulates, is in thermal contact with the end of the copper sheets which envelop the detector slabs, and also with the DIF card whose on-board electronics produce heat.

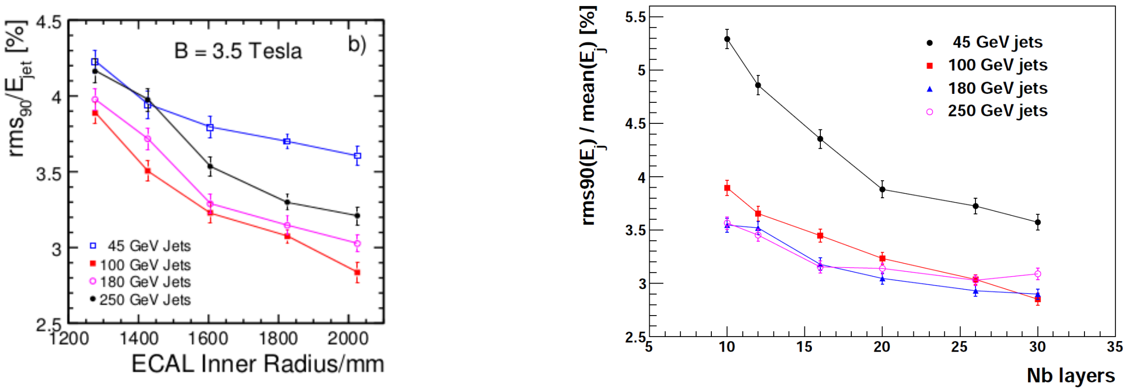

Figure 2: The jet energy resolution performance of ILD at various jet energies as a function of the ECAL inner radius (left, from [7]), and the number of ECAL layers (right, from [3])

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5. Optimisation studies

Such an ECAL would represent a significant fraction of the cost of a future ILD-like detector. This cost is driven by the large surface of silicon sensors required, $\sim 2500\text{m}^2$ in the default design. It is therefore important to understand the effects on detector performance of choosing a less costly design. Some aspects of the design have proved challenging to engineer. The effect of less aggressive design choices should also be investigated. The metrics used to quantify these effects are typically the energy resolution for single photons and the jet energy resolution achieved after application of the Pandora Particle Flow Algorithm [5].

The large area of silicon sensors is due to the large dimensions of the ECAL and the number of sampling layers used within it. Figure 2 shows the dependence of the jet energy resolution on the inner radius and number of layers in the ECAL. Both distributions do show some detrimental effect of reducing the silicon area, however, the loss in performance from a moderate decrease in area may be acceptable given the financial saving that may be possible.

The transverse segmentation of the ECAL affects the total number of readout channels and front end ASICs required, which will have a non-negligible effect on the detector cost. A larger channel density will also provide additional challenges in the design of the PCB. The effect of increasing the pixel size from 5×5 mm to 10×10 mm has a significant effect on the jet energy resolution, in particular for the more energetic jets at or above 180 GeV [7].

The required quality of silicon sensors may also have an effect on the ECAL cost. If a few bad channels (e.g. channels with a high leakage current and therefore small dynamic range) are allowed per sensor, industrial yields may increase, and cost per sensor decrease. A study on the effect of dead pixels has been performed, assuming that such pixels are randomly distributed throughout the calorimeter. As shown in Fig. 3 (left), the effect of even up to 10% dead pixels has only a rather small effect on the jet energy resolution, although the effect on the single photon energy resolution is significant.

Other aspects of the design, such as the sensor's guard ring and the PCB, which should both be as thin as possible from a physicist's perspective, pose engineering challenges. The thickness of

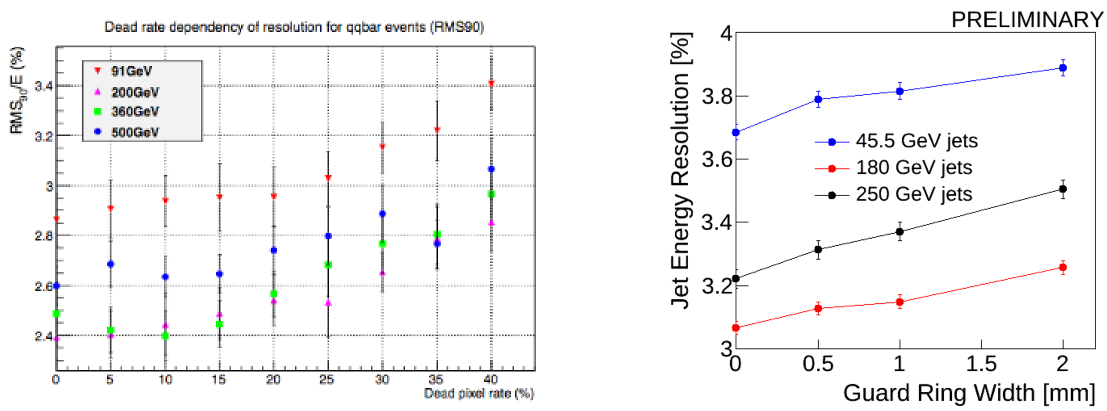

Figure 3: The effect of the dead pixel fraction (left) and silicon sensor guard ring thickness (right) on the jet energy resolution performance of ILD.

the PCB has very little effect on detector performance (although the total thickness of the ECAL will also increase, pushing the HCAL, solenoid and yoke to larger radii), while increasing the guard ring width (and the dead area associated with it) does has a relatively weak effect on the jet energy resolution, as shown in Fig. 3 (right).

6. Summary

An ECAL based on tungsten absorber and silicon sensors can satisfy the requirements presented by event reconstruction at a future linear collider. The design of such an ECAL for the ILD has been developed with the requirements of (semi-)industrialised manufacture and quality control in mind, as well as the requirements from physics. The effect of various design choices on detector performance and cost are now being evaluated before a final design is produced.

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