A Silicon-Tungsten Electromagnetic Calorimeter with Integrated Electronics for the International Linear Collider

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Abstract. We present an update of the development of an electromagnetic calorimeter for the Silicon Detector concept for a future linear electron-positron collider. After reviewing the design criteria and related simulation studies, we discuss progress in the research and development of the detector. This concept has from the outset made the case for highly integrated electronic readout with small (1 mm) readout gaps in order to maintain a small Molière radius for electromagnetic showers and to avoid active heat removal. We now have fully functioning 1024-channel readout chips which have been successfully bonded to 15 cm silicon sensors. We present initial results from these assemblies.

1. Introduction

The Silicon Detector (SiD) is a general purpose detector designed to conduct precision physics measurements of high energy $e^+e^-$ collisions at the International Linear Collider (ILC). The baseline design uses a Particle Flow Algorithm-based (PFA) approach to calorimetry. PFAs have been successfully applied to existing detectors, such as CDF, ZEUS, and CMS and have resulted in significant improvements of the jet energy resolution compared to methods based on calorimetric measurement alone. However, these detectors were not originally designed with the application of PFAs in mind. The SiD baseline design on the other hand considers a PFA approach necessary to reach the goal of obtaining a measurement uncertainty on the jet energy resolution of the order of 3% or better. SiD is therefore optimized assuming the PFA approach and the major challenge imposed on the calorimeter by the application of PFAs is not the intrinsic calorimetric energy measurement of either the electromagnetic calorimeter (ECAL) or the hadronic calorimeter (HCAL), but the association of energy deposits with either charged or neutral particles impinging on the calorimeter. This results in several requirements on the calorimeter design:

- To minimize the lateral size of electromagnetic showers the Molière radius of the ECAL must be minimized. This enables efficient separation between photons and electrons and charged hadron tracks.
Both ECAL and HCAL must have imaging capabilities which allow assignment of energy cluster deposits to charged or neutral particles. This implies that the readout of both calorimeters needs to be finely segmented transversely and longitudinally.

- The calorimeter needs to be extendable to small angles to ensure hermeticity.

2. Requirements
The major challenge imposed on the calorimeter by the application of PFAs is the unambiguous association of energy depositions in the calorimeters with the showers originating from individual particles. For the ECAL, this implies that electromagnetic showers be confined to small volumes in order to avoid overlaps. Effective shower pattern recognition is possible if the segmentation of readout elements is small compared to the showers. This level of transverse segmentation then also facilitates the separability of the electromagnetic showers from charged particle tracks due to un-interacted charged hadrons (and muons). The longitudinal segmentation is chosen not only to achieve the required electromagnetic energy resolution, but also to provide discrimination between electromagnetic showers and those hadrons which interact (typically deeper) in the $\approx 1$ interaction length of the ECAL. Finally, there should be a sufficient number of longitudinal readout layers to provide charged particle tracking in the ECAL. This is important not only for the PFA algorithms, but also to aid the tracking detectors, especially for tracks which do not originate from the primary beam interaction point.

3. Global ECAL Design
A sampling ECAL provides adequate energy resolution for the ILC physics, as discussed above. Because of its small radiation length and Molière radius, as well as its mechanical suitability, we have chosen tungsten as the absorber/radiator. Due to practical considerations for ease of production of large plates and machining, the tungsten will be a non-magnetic alloy. The currently chosen alloy includes 93% W with radiation length 3.9 mm and Molière radius 9.7 mm. An additional benefit of tungsten is that it has a relatively large interaction length, which helps to minimize confusion between electromagnetic and hadron showers in the ECAL.

The longitudinal structure we have chosen has 30 total layers. The first 20 layers each have 2.50 mm tungsten thickness and 1.25 mm readout gap. The last 10 layers each have 5.00 mm tungsten plus the same 1.25 mm readout gap. This configuration attempts to compromise between cost, shower radius, sampling frequency, and shower containment. The cost is roughly proportional to the silicon area, hence the total number of layers. We chose finer sampling for the first half of the total depth, where it has the most influence on electromagnetic resolution for showers of typical energy. The total depth is $26X_0$, providing reasonable containment for high energy showers. Simulations have shown the energy resolution for electrons or photons to be well described by $0.17/\sqrt{E}$.

Silicon detectors are readily segmented, and in the baseline design we have chosen there is little penalty for segmenting the silicon sensors much more finely than typical shower radii. As discussed above, the scale for this is set by the shower size, which we wish to be as small as feasible. A useful figure of merit for this is the Molière radius, which is 9 mm for pure tungsten. Since showers will spread in the material between tungsten layers, it is crucial to keep the readout gaps as small as possible. Our design results in an effective Molière radius of 14 mm.

4. Sensor and Readout Technology
In the baseline design, the ECAL readout layers are tiled by large, commercially produced silicon sensors (presently from 15 cm wafers). The sensors are segmented into pixels which are individually read out over the full range of charge depositions. The complete electronics for the pixels is contained in a single chip, the kPiX ASIC, which is bump bonded to the wafer. We
take advantage of the low beam-crossing duty cycle \((10^{-3})\) of the ILC to reduce the heat load using power pulsing, thus allowing passive thermal management within the ECAL modules. The realization of this technology has been the subject of an intensive, ongoing R&D program. The main parameters associated with the baseline technology choice are given in Table 1.

| Parameter                               | Value          |
|-----------------------------------------|----------------|
| readout gap (incl. Si sensor)           | 1.25 mm        |
| effective Molière radius                | 14 mm          |
| pixel area                              | 13 mm²         |
| pixels per silicon sensor               | 1024           |
| dynamic range requirement               | ~ 0.1 to 2500 MIPs |
| heat load requirement                   | 20 mW per sensor |

Figure 1 shows a sensor with 1024 pixels. Not shown in the drawing are the signal traces, part of the second layer metallization of the sensors, which connect the pixels to a bump-bonding pad at the center of the sensor for input to the kPiX readout chip. The pixels are DC-coupled to the kPiX, thus only two metallization layers are required for the sensors. The pixels near the bump-bonding array at the center are split to reduce capacitance from the large number of signal traces near the sensor center. The electronic noise due to the resistance and capacitance of the traces has been minimized within the allowed trace parameters. The cutouts at the corners of the sensor are to accommodate mechanical stand-offs which support the gaps between the tungsten layers.

Figure 2. Drawing of an individual silicon sensor for the ECAL. The sensors are segmented into 1024 13 mm² pixels.

After several iterations with the R&D, in early 2012 a full 1024-channel kPiX was successfully bump-bonded to a sensor by IZM Company. Following this, a kapton cable was successfully bump-bonded to the sensor assembly at UC Davis. The cable bonding uses a lower temperature solder than that used for the kPiX bonding. Figure 3 shows the fully bonded assembly, along with a closeup of the kPiX chip in Figure 4.
5. Bonded sensor results

Initial bench tests of the bonded sensor of Figure 3 have been carried out and the results are quite promising. A cosmic ray telescope was used to trigger kPiX and the charge of the pixel having the maximum charge was entered in the distributions shown in Figure 5. The red distribution resulted when the ECAL sensor was placed within the telescope acceptance, while the blue distribution resulted when the sensor was outside the telescope acceptance. A Landau distribution (black) is fit to the red signal. The peak of the signal at about 4 fC is consistent with our expectation for minimum-ionizing particles (MIP) passing through the fully-depleted 320 µm thick sensors.

With the highly integrated design we have chosen, a potential worry is crosstalk between channels. Figure 6 indicates no evidence for crosstalk in any other channel when a large 500 fC signal is injected. The noise distribution is nicely fit by a gaussian with RMS 0.2 fC. This is to be compared with the 4 fC MIP signal. This noise level exceeds our requirements for the ECAL.

**Figure 3.** Photograph of a fully bonded sensor. The kPiX chip is bump-bonded to the sensor. Power, control and readout signals are provided via the kapton cable.

**Figure 4.** The central region of a sensor showing the kPiX chip. The slots in the kapton allow for differential thermal expansion.

**Figure 5.** Distribution of charge depositions in a bonded sensor for cosmic ray triggered events. The MIP peak is clearly visible above the noise peak.

**Figure 6.** Crosstalk test of a bonded sensor. The charge distributions for all non-pulsed pixels are compared for a large pulse injection (red) and no pulse injection (blue). Also shown is a gaussian fit with RMS 0.2 fC.
6. Overall Mechanical Design

Figure 1 displayed the overall mechanical structure of the ECAL barrel, showing the overlapping stave geometry which is designed to minimize any uninstrumented regions, especially any projective gaps. Figure 7 depicts a cross-sectional view of the readout gap in the vicinity of the center of a wedge module. Kapton flex cables connect near the center of the sensors, bringing power and control signals into the kPiX chip and returning the single digital output line for the 1024 channels. These signals are then multiplexed at the ends of the modules.

Thermal management is a crucial feature of this design. The most power hungry elements of the kPiX chip, particularly the analog front end, are switched off for most of the interval between bunch trains. Our requirement is to hold the average power dissipation per wafer to less than 40 mW. This will allow the heat to be extracted purely passively, providing a much simpler design, less subject to destructive failure modes. The design of the kPiX chip in fact gives average power less than 20 mW, resulting in a total heat load per wedge module of 115 Watt. A cold plate with water pipes routed laterally at the outside of the wedge as shown in Figure 8 results in a maximum temperature differential of $1.35^\circ$C.

![Figure 7. Cutaway of the SiD ECAL Barrel wedge, showing the Si sensor and readout cable layout.](image1)

![Figure 8. SiD ECAL Barrel wedge, showing the cooling elements, which are located at the outer radius of the barrel.](image2)

Referring to Figure 7, the construction of a barrel “wedge” module is carried out as follows. Because tungsten plates are only available with a maximum size of $1 \times 1$ m$^2$, the wedge assembly is done by interconnecting the plates with a screw-and-insert network, which transfers the load from the bottom of the stack to the rail. The design is self-supporting and it does not require additional material to provide the required stiffness. The assembly procedure for a single wedge is sequential with the sensors permanently captured in the gap between tungsten plates, which are specified to have high planarity, achieved at the vendor site by grinding. This specification has been verified on a batch of $15 \times 15$ cm$^2$ plates procured for the beam test module, which have planarity tolerances of $\pm 10\mu m$, and have been confirmed by interviewing several tungsten vendors/producers. Because of the trapezoidal cross-section of the wedge, the assembly sequence is bottom up, with the wider plate at the base. The first layer of tungsten will be laid down on a jig tool to set the basic tolerances of the stack. Spacing inserts are placed at the locations of the cutouts at the sensor edges (see Figure 2), followed by the sensors with flex cables.

The control of the gap tolerances relies on the flatness of the tungsten plate and on the spacers, whose quality is individually controlled by metrology. The positioning tolerances of the sensor modules in the plane rely on the quality control of not only the spacers, but also on the flex-cable, which will have mounting pads which mate with the inserts. The assembly of the
sensors on the flex-cable will be done on a precision jig, which will guarantee the repeatability of the assigned tolerances. The second layer of tungsten will be overlaid on the sensors, once mechanical and electrical connection are tested. This process is repeated 30 times along the stack, which is the number of the active layers of a single wedge module. The last plate on the top has rails, which will allow the insertion and the support from the HCAL. Prior to insertion, each individual wedge will be equipped with a cold plate for thermal management, running along \( z \) on one side of the wedge. The boxes on the two opposite sides at \( \pm z \) contain the data concentrator electronics, which completes the assembly.

7. Prototype Module and Test Beam

Given the positive initial results of the first bonded sensors, we are moving forward with our plans to build a full-depth test module. This is shown in Figure 9. The test stack is to have a width of one sensor, easily sufficient to contain electromagnetic showers. The longitudinal structure closely matches that of the SiD ECAL. The main difference is that we will have 1.5 mm readout gaps for the test stack, rather than the nominal 1 mm gaps of the SiD design, in order to allow clearance for sensor assemblies to be slid in or out of the stack.

Since the operation of kPiX has been optimized for the bunch timing structure of the ILC, the optimal test facility would be an electron beam having a similar timing structure. Fortunately, SLAC is presently restoring a test beam capability at End Station A. We expect to have the sensors for the test module prepared and first data from this facility in 2013.

![Figure 9. Schematic of a test module to be tested in a beam. The module has a width of one sensor and a depth of 30 layers. The kapton cables attached to each sensor feed concentrator boards, which in turn are connected to a mother board.](image)

8. Calibration and alignment

Silicon detectors are inherently insensitive to gain variations with time and should not have significant inter-pixel gain differences. Pixel to pixel gain differences in the electronic readout are calibrated by dedicated calibration circuitry within the kPiX chip. Perhaps the main calibration issue will be sensor to sensor gain differences. These are not expected to be large, but we are investigating different options for this calibration.

Alignment within ECAL modules and between modules should not be difficult to control with careful fabrication. Alignment to the inner detectors can be sufficiently established using charged particle tracks.