R&D for a SiW Electromagnetic Calorimeter for a Future Linear Collider

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Abstract. This article presents an overview on the status and perspectives of a highly granular silicon tungsten electromagnetic calorimeter (SiW Ecal) conceived for the operation at a future linear electron-positron collider. Prototypes for this kind of calorimeters are developed within the R&D program of the international collaboration CALICE. This article reports on results on the "pure" calorimetric performance of a first physics prototype with an energy resolution of about $17\%/\sqrt{E}$ and an angular resolution of about 100 mrad. Beyond that, emphasis is put on the merits of the high granularity which is indispensable for the achievement of the envisaged physics goals of a linear collider. This high granularity permits the application of image processing algorithms for particle separation as well as it reveals a more detailed view into hadronic cascades than was possible hitherto.

1. Introduction
The next major worldwide project in high energy particle physics will be a linear electron positron collider at the TeV scale. This machine will complement and extend the scientific results of the LHC currently operated at CERN. The most advanced proposal for such a machine is the International Linear Collider (ILC) which will be operated at centre-of-mass energies between 90 GeV and 1 TeV. The experimentation at this machine could start around the year 2020. Introductions to the concept of the ILC and to the alternative for higher energies CLIC, short for Compact Linear Collider concept, can be found elsewhere [1, 2]. The article will focus on the status and prospects of the R&D for an electromagnetic silicon tungsten calorimeter.

2. Requirements for ILC Detectors
The well known initial state of the electron positron collisions is an ideal premise for high precision measurements at a linear collider. The extremely rich physics potential puts high requirements on the detector performance. One driving force for the detector optimisation is an optimal separation of jet final states created W and Z bosons. This measurement would become particular important in the absence of the Higgs boson which would then require a new type of interaction in order to preserve unitarity. Other important measurements would be the couplings of the Higgs boson to fermions, in particular to quarks which turn into jets.
The reconstruction of the final state of the $e^+e^-$ interactions will be based on particle flow algorithms (PFA) [3, 4]. The goal is to reconstruct every single particle of the final state which in turn demands a perfect association of the signals in the tracking systems with those in the calorimeters. As a consequence, this requires a perfect tracking of the particle trajectories even in the calorimeters. The jet energy resolution, a direct measurement for the detector performance, is then mostly given by residual overlap, also called confusion, of signals from near by particles in the final state. The concept of particle flow and the aim of resolving the jet energy $E_{\text{jet}}$ to a value of $\sigma_{E_{\text{jet}}} / E_{\text{jet}} \approx 4\%$ lead to a challenging novel detector design.

The calorimeters have to feature an unprecedented high granularity. For an optimal particle flow, they will have to be placed inside the magnetic coil of the detector which puts tight constraints on the space available for the installation of the detectors. The design of the calorimeters have thus to follow two main guidelines:

- The number of readout channels has to be driven to an unprecedented amount.
- The calorimeters have to be extremely compact and hermetic. This concerns both, the choice of the absorber material and the integration of infra-structural components such as cooling, power supply, readout lines and front end electronics.

For the electromagnetic calorimeter which surrounds the tracking system the two guidelines above lead to the choice of tungsten as absorber material having a radiation length $X_0 = 3.5 \text{ mm}$, Molière radius $R_M = 9 \text{ mm}$ and interaction length $\lambda_I = 96 \text{ mm}$ and silicon as the active material.

The CALICE collaboration [5], short for CAlorimeter for a LInear Collider Experiment, conducts a large R&D program for the development of highly granular calorimeters as envisaged for the detectors of a linear collider. CALICE comprises 336 physicists and engineers from 17 countries and 4 continents. A physics prototype of the SiW Ecal dedicated mainly to demonstrate the physics potential of a calorimeter fulfilling the requirements above but also to validate the main mechanical concepts has been constructed and is currently examined in beam test measurements at DESY, CERN and FNAL. The results of the beam test data taking with the physics prototype as well as the steps towards the realisation of its successor, a technological prototype, will be described in the following sections.

3. The Physics Prototype

The physics prototype [6] is dedicated to demonstrate the principle of compact high granular calorimeters. Its major purpose is to verify physics observables like energy resolution and angular resolution to support the validity of the ongoing physics studies with a full detector. Another important objective of the program with the physics prototype is the verification of models of hadronic showers. These are typically less well modelled than electromagnetic showers and the uncertainty can be estimated from the fact that the simulation toolkit GEANT4 [7] offers more than 10 different models for these hadronic showers. The Figure 1 shows a lateral view of the physics prototype. It consists of 9720 $1\times1 \text{ cm}^2$ wide calorimeter cells in 30 layers. The active zone covers $18\times18 \text{ cm}^2$ in width and approximately $20 \text{ cm}$ in depth. The layers are composed alternately by W absorber plates and a matrix of PIN diode sensors on Silicon Wafer basis. At normal incidence, the prototype has a total depth of $24 X_0$ achieved using 10 layers of $0.4 X_0$ tungsten absorber plates, followed by 10 layers of $0.8 X_0$, and another 10 layers of another $1.2 X_0$ thick plates. The sensitive layers are mounted onto both sides of a H-shaped tungsten plate as shown in Figure 2. Such an entity is called a slab. The readout electronics sticks out to the left of the sensitive area.
3.1. Beam test data taking

The physics prototype was subject to large scale beam test data taking in the years 2006-2008. In these beam test campaigns about $10^8$ events have been recorded with electron, pion and muon beams.

The Figures 3a and 3b show the response of the prototype to electrons in terms of linearity and energy resolution [8].

![Figure 1: Schematic 3D view of the Physics Prototype. Figure taken from [6].](image1)

![Figure 2: Schematic diagram showing the components of a detector slab. Figure taken from [6].](image2)

Figure 3: (a) Linearity of the energy response of the SiW Ecal as a function of the nominal energy. (b) Relative energy resolution $\sigma(E_{\text{meas}})/E_{\text{meas}}$ as a function of $1/\sqrt{E_{\text{beam}}}$ (solid squares), and its usual parameterisation as $s/\sqrt{E} + c$. The values expected from simulation are shown (open squares).
The results are based on an analysis of data taken in the year 2006 at CERN. Both observables are well described by a GEANT4 Monte Carlo simulation of the beam test setup. It is found that between 6 and 45 GeV the detector response is linear within 1%. The energy resolution is determined to be

\[
\frac{\sigma(E_{\text{meas}})}{E_{\text{meas}}} = \left( \frac{16.53 \pm 0.14(\text{stat}) \pm 0.4(\text{syst})}{\sqrt{E(\text{GeV})}} \oplus (1.07 \pm 0.07(\text{stat}) \pm 0.1(\text{syst})) \right) \%, \quad (1)
\]

For the angular distribution the following values are reported [9]:

\[
(106 \pm 2)/\sqrt{E} \oplus (4 \pm 1) \text{ mrad along the x-direction and} \\
(100 \pm 2)/\sqrt{E} \oplus (14 \pm 1) \text{ mrad along the y-direction.}
\]

The differences between the two directions can be explained by the different arrangement of the detector layers in \(x\) and \(y\) direction.

3.1.1. Calibration of the SiW Ecal
The details of the calibration procedure are presented in [6]. The relative calibration was performed using dedicated muon beams with an energy of up to 120 GeV, i.e. in a regime in which muons are expected to lose their energy only by ionisation and act, to a good approximation, as minimal ionising particles (MIP).

The results of the calibration reported here are valid for the data taking period 2006 in which 18 M. calibration events were recorded. The findings are however confirmed in [10]. The MIPs deposit and energy equivalent to around 45 ADC Counts in units of the CALICE Data Acquisition system. According to [6], this translates into a signal to noise ratio of 7.5:1. The Figure 4 demonstrates the uniform response of all calorimeter cells. Residual variations can be assigned to different manufacturers (different colours) and production series of the silicon wafers. In 2006, only 1.4% of the around 6500 cells produced up to that year were found to be non-operational.

With respect to the operation in a detector at a linear collider, the stability of the calibration is an important issue. A good indicator to address this question is the comparison of calibration constants obtained in different test periods. The Figure 5 shows the good linear correlation between the calibration constants as obtained for the CERN running in October 2006 and the set of calibration constants obtained in running period two months earlier. Additionally, the constants from October 2006 are compared with those of a test bench measurement prior to the actual beam test data taking.

4. Exploiting the High Granularity
This section focuses on studies which explore the unprecedented high granularity of the SiW Ecal. As will be shown in the following, this granularity leads to a high power for the separation of close by particles [11] as well as for detailed insight into hadronic showers [12]. The results presented here are obtained with the Physics Prototype.

4.1. Particle Tracking
The final state of the \(e^+e^-\) collisions leads partially to overlapping particles in the electromagnetic calorimeter. On the other hand, the success of the Particle Flow algorithms
Figure 4: Equivalent ADC value $G_L$ for the energy deposit of a MIP in the Ecal prototype, obtained using the October 2006 muon events sample, as a function of the pad index. The inset histogram displays the projection on the y-axis.

Figure 5: (a) Calibration constants obtained with August 2006 muon runs versus those obtained with October 2006 muon runs. The colour scale represents the number of entries per bin. (b) Mean per chip of the calibration constants obtained with the cosmics test bench versus those obtained with October 2006 muon runs, discarding two outliers. The ADC counts represented in both axis are obtained with different DAQ systems.

is based on the clean separation of signals from different particles. The high granularity of the SiW Ecal leads naturally to a rich amount of information which can be exploited using advanced e.g. imaging processing techniques. One of these techniques is the Hough transformation [13]. The Hough transformation provides a mapping from a $n$-dimensional feature space onto a $m$-dimensional parameter space, also called Hough space. In short words, points which are on a straight trajectory as e.g. generated by a MIP, will all result into the same parameter set in the Hough space. Thus, by subjecting the calorimeter cells
which carry energy at or above one MIP to a Hough transformation, a MIP trajectory will lead to an accumulation at a given set of parameters. Figure 7 illustrates the merits of the Hough transformation and thus of the high granularity.

Figure 6: Examples for overlay events as observed in beam tests. The left plot shows an overlay of most probably two pions. (Selected hits are marked by red and green points). The right plot shows an electron signature and a MIP track (red points).

Here, two examples for the separation of two close by particles are given. More quantitatively, the Figure 7a shows that a 100% detection efficiency of the MIP track is provided for fractions of shared hits of up to 50%. This result is independent of the hits actually generated by the primary MIP. At the same time, Figure 7b demonstrates that a full separation of close by particles can be achieved for distances down to 2.5 cm.

Figure 7: (a) MIP detection efficiency as a function of the MIP/shower proximity $\kappa$. The detection efficiency is broken down for different minimal numbers (red 10, green 20, blue 30) of true hits induced by the MIP. (b) MIP detection efficiency as a function of particle distance.
4.2. Hadronic Showers in the Ecal

Given the depth of about one interaction length, about 55% of the hadrons contained in a jet will interact in the volume of the SiW Ecal. It is therefore important to understand the interactions of hadrons in the SiW Ecal.

Exploiting the longitudinal granularity of the calorimeter, the interaction point of interactions of primary hadrons can be identified by comparing energy depositions and hit densities in subsequent detector layers. The correlation between the reconstructed and the true interaction point as available from Monte Carlo simulation is shown in Figure 8a. A good correlation can be reported. Interaction layers as found in data and in Monte Carlo simulation are compared in Figure 8b. Here, the QGSP_BERT(ini) physics list as implemented in GEANT4 is used. For an overview on the various physics list see [14]. The good agreement found in this case holds also when testing other GEANT4 physics lists.

![Figure 8](image)

(a) Figure 8: (a) Comparison between reconstruction and truth for the layer identified as the interaction layer. This example corresponds to a 20 GeV $\pi^-$ beam simulation, using the QGSP_BERT physics list. (b) Distribution of the reconstructed interaction layer in the Ecal for 30 GeV data (points), compared with Monte Carlo predictions using the QGSP_BERT physics list (solid histogram).

The amount of overlap of showers generated by close by particles is governed by the transversal shower radius of the particles. In turn it is easy to understand that the amount of overlap influences directly the precision which can be achieved by PFA algorithms. It is thus of major importance that the transverse properties of a hadronic shower are well modelled by Monte Carlo simulations. The Figure 9 shows the comparison of the transverse shower profile for 8 GeV and 30 GeV pions incident on the calorimeter surface. Again, the default physics list is chosen to be QGSP_BERT.

The mean values of the introduced transversal profiles for several physics lists and energies are given in Figure 10. From here and from the earlier result it can be concluded that those models which implement the Bertini cascade [15] give a good description at small energies. At high energies, all models however predict smaller shower radii than observed.

The longitudinal profile is composed by contributions from several components. The Figure 11 shows the longitudinal profile as a function of the shower depth after the interaction...
Figure 9: Radial distribution of hits (energy weighted) for data at energies of 8 and 30 GeV (points with errors) compared with Monte Carlo (solid histograms) using the QGSP_BERT physics list. The distributions are normalised to unity.

Figure 10: Mean energy-weighted shower radius in the Ecal as a function of beam energy. The data are compared with the predictions of simulations using different GEANT4 physics lists.

point for pions with an energy of 12 GeV compared with the predictions obtained by the QGSP_BERT and FTFP_BERT models.

The profile of the Monte Carlo prediction is broken down into its various components. It is clearly visible that there are significant differences between the models and the data and between the models themselves. This is particularly true for short range components generated by heavily ionising particles such as protons. This first separation into various domains of the shower is continued in the study presented in Figure 12. Here the energy depositions in different layers after the interaction point are shown in greater detail. Again, the early stages of the shower created by nuclear break-up are not well described by either of the models. On the other hand all models, but the one dubbed LHEP, lead to a reasonable description of the energy deposition for larger shower depths. The said is particularly true for the models which feature the Bertini cascade.

5. Construction of a Technological Prototype

The next prototype, also called EUDET Module, has been conceived during the year 2008 and enters now its construction phase. It addresses, more than the first prototype, the engineering
challenges which come along with the realisation of highly granular calorimeters. The key parameters of the new prototype are

- Size of an individual cell of 5.5x5.5 mm$^2$.
- A depth of 24 $X_0$.
- Thickness of an individual layer of 3.4 mm and 4.4 mm according to the position within the calorimeter.

The Figures 13 and 14 show the mechanical housing and a cross section through two calorimeter layers which form a slab. The mechanical housing is realised by a tungsten carbon composite, which provides at the same the absorption medium and the mechanical rigidity of the detector. The silicon wafers are composed of high resistive silicon. While in principle the manufacturing of these wafers is a well known technique the challenge is to produce these wafers at small price in order to reduce the cost since a surface as large as 3000 m$^2$ will be needed for a linear collider detector. The final calorimeter will comprise around $10^8$ channels in total. In order to reduce the non-equipped space in the detector the very front end electronics (VFE) has to be integrated into the calorimeter layers, see Figure 14, which constitutes a major challenge for the construction of the calorimeter. The room available for the readout circuits (ASICs) and the interface boards between the ASICs and the silicon wafers is about a millimetre.

Each of the ASICs of the new prototype will readout 64 calorimeter cells and realises the measuring of the analogue signal, the digitisation and the zero suppression such that only a limited number of channels are finally send to the data acquisition which is based on custom made components in order to allow for the employment of large quantities at reasonable prices for the experimentation at the linear collider.

Due to the limited space available for cooling devices the heat dissipation of the ASICs has to be minimised. In addition to the cooling, the heat dissipation will be reduced by a novel technique called "Power Pulsing". Here, the VFE will only be switched on during the millisecond of a bunch train of particles. Such a bunch train contains about 3000 particle

![Figure 11: Longitudinal energy profiles for 12 GeV $\pi^-$ data (shown as points), compared with simulations using two physics lists. The mean energy in MIPs is plotted against the depth after the initial interaction, in units of effective 1.4 mm tungsten layers. The total depth shown corresponds to $\sim 20 X_0$ or 0.8 $\lambda_{int}$.

The breakdown of the Monte Carlo into the energy deposited by different particle categories is also indicated.](image)
bunches separated by around 300 ns. During the around 200 ms between these bunch trains, the electronics will be switched off. Clearly, this novel technique will require detailed studies in order to assure that the signal quality of each channel remains constant after each powering cycle. The first ASICs which incorporate the power pulsing are tested during the year 2010.

A calorimeter layer will have a length of about 1.5 m and will be composed by several units which carry silicon wafers as well as the VFE. The challenge is to integrate this fragile assembly into the alveolar structure which houses the calorimeter layers. The integration cradles are under development and a first integration test with a demonstrator has been
successfully conducted in October 2009.

Figure 13: Alveolar structure and its dimensions which houses the sensitive parts of the CALICE SiW electromagnetic calorimeter prototype.

Figure 14: Cross Section through a slab for the CALICE SiW electromagnetic calorimeter prototype.

6. Summary and Outlook

High precision measurements with a detector at a linear electron-positron collider at the TeV scale will be based on Particle Flow. Its application requires highly granular calorimeters. The current baseline of detectors proposed for the International Linear Collider feature a highly granular silicon tungsten (SiW) electromagnetic calorimeter with a lateral segmentation of $5 \times 5 \text{mm}^2$ and a longitudinal depth of $24 \times 0$ subdivided into 30 layers comprising approximately $10^8$ cells in total. Between the years 2005-2008 a physics prototype with 10000 cells built to demonstrate the principle of highly granular calorimeters was operated successfully by the CALICE collaboration in several large scale test beam campaigns. The physics prototype will be succeeded by a larger technological prototype which addresses technological challenges as for example the power pulsing of the front end electronics. From the operation of the physics prototype and the first steps towards the technological prototype, it can already be concluded that it will be feasible to operate a highly granular SiW Ecal in a detector for a linear collider. This conclusion is based on the following facts:

- The signal to noise ratio is of the order of 8 which is given the early stage of the R&D already very close to the envisaged goal of 10.
- The energy resolution is approximately $17\% / \sqrt{E}$ and the angular resolution is about $(100 \text{ mrad}) / \sqrt{E}$. These results confirm the values used e.g. in the Letter of Intent studies for the ILD detector [16]. Ongoing studies put more emphasis on exploiting the highly granular structure of the device. In that sense, the study of details of hadronic showers as well as the optimisation of the separation of individual particles are important steps into that direction.
- By comparing data taken in different years at different locations, it could be demonstrated that the calibration is very stable over several years of operation. This is one of the key points required for the validation of the detector concepts.
• It will be possible to realise the challenging mechanics based on self-supporting alveolar structures which incorporate half of the tungsten absorbers. This was proved by the construction of a mechanical demonstrator.

• The readout electronics will be integrated into the layer structure of the calorimeter and has to integrate a multitude of tasks from first stage amplification until on-chip zero suppression and digitisation. The current status of the R&D shows that these challenging ASICs can be built. Preliminary studies indicate that the embedding of the ASICs into the layer structure will not compromise the precision measurements. One key design element for the ASICs is low power consumption. The goal is to achieve 25 $\mu$W/channel using power pulsing. Residual heat will be evacuated by a dedicated cooling system of which a first prototype was operated successfully in the context of the studies with the mechanical demonstrator.

• The technology for the silicon wafers is at hand [17]. Shortcomings observed during the operation of the physics prototype like square events could be remedied by dedicated modifications of the guard rings which surround the silicon wafers. :

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