CALICE Proposal 317

Calorimetry for the Interational Linear Collider

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1 Introduction

The CALICE collaboration is studying calorimetry for the future e^+e^- international linear collider (ILC) in the 500-1000 GeV centre-of-mass energy range. The physics of the ILC demands calorimetry capable of delivering high resolution for hadronic jet energies. CALICE is the only collaboration within the ILC community studying both electromagnetic (ECAL) and hadronic (HCAL) calorimeters in an integrated way and believes this overall calorimetry approach is the only way to obtain a calorimeter system which will be capable of meeting the demanding physics requirements of a high energy ILC detector. It aims to be at the forefront of ILC calorimetry development by the time any detector collaboration is formed. The CALICE program covers beam tests of several technologies and simulation studies based on the results of these tests, so as to design a ILC calorimeter optimised for both performance and cost.

2 The International Linear Collider

The ILC is a worldwide enterprise to construct an $\mathrm{e}^+\mathrm{e}^-$ linear collider operating in the energy range 0.5 to 1 TeV, which will complement the LHC [1]. In broad-brush terms, the LHC will be a powerful discovery machine to reveal the new physics which is expected to emerge on the TeV scale in, for example, the Higgs and supersymmetry sectors, while the ILC will be better adapted to performing high precision tests. A major item of progress in the past year was the establishment of an International Technology Recommendation Panel, to advise the community on the technology to pursue. In August 2004 this panel recommended the adoption of superconducting technology [2]. Efforts around the world are now directed towards jointly producing a fully costed accelerator technical design by 2007.

Amongst the main physics areas to be addressed by the ILC will be precise measurements of Higgs boson properties, accurate investigation of the SUSY spectrum, probing of strong electroweak symmetry breaking, and precision top quark physics. A common requirement for most of these physics studies is good measurement of hadronic jet energies, and this places stringent requirements on the calorimetry. There is general agreement that the way to achieve the required jet energy precision is via the “Particle Flow” (aka “Energy Flow”) paradigm. This requires the energy deposits of different particles in the calorimeters to be separated, which in turn leads to an emphasis on granularity and spatial resolution rather than single-particle energy resolution. These granular detectors are often referred to as “tracking calorimeters”. It also demands a holistic approach to the detector design, where the interrelationship between different components of the detector is taken into account from the beginning. This is the approach taken by the CALICE collaboration.

3 The CALICE Collaboration

The Calice collaboration [3] is undertaking a major programme of R&D into calorimetry for the ILC. It now has 167 members from 26 institutes worldwide and is by far the largest group studying calorimetry for the ILC.

The collaboration intends to test pre-prototypes of an electromagnetic calorimeter (ECAL) along with at least two types of hadronic calorimeter (HCAL) in electron and hadron beams over the next two years. The Calice programme also covers simulation studies incorporating the results of these tests, all directed towards the design of an ILC calorimeter optimised for both performance and cost. In addition, the collaboration serves as an umbrella organisation for longer-term ILC calorimeter projects where developments can be tested together.

One of the main motivations for Calice is to verify the simulation programs, particularly for hadronic showers, such that the design and optimisation of the final ILC detector calorimeters can be done using these simulation programs with confidence. The optimisation is not purely for physics performance; for example, cost is one of the main constraints for the favoured ECAL design, which is a silicon-tungsten (Si-W) sampling calorimeter. The cost of the large area of silicon wafers required is high and so studies to reduce this cost, in terms of less area or cheaper alternatives, are a major part of this programme.

The Calice ECAL prototype is a silicon-tungsten sampling calorimeter and consists of 30 layers of silicon wafers interspersed between tungsten sheets. Each wafer layer contains a 3×3 array of silicon wafers, each containing 36 $1 \times 1\,\mathrm{cm}^2$ diode pads. There are around 10,000 channels in total occupying a volume of approximately $(18\,\mathrm{cm})^3$. The ECAL assembly is currently paced by the silicon wafer production; more than half of the silicon wafers are now manufactured and the rest are expected over the next three months. Around one third of the layers were ready by the end of 2004 and the rest are expected to be complete by April 2005.

The analogue HCAL (AHCAL) is a sampling calorimeter with 40 layers of steel absorber sheets instrumented with scintillator tiles. The total volume is approximately $(1\,\mathrm{m})^3$. The tiles are of varying sizes, with the highest granularity central region using $3 \times 3\,\mathrm{cm}^2$ tiles, increasing to $12 \times 12\,\mathrm{cm}^2$ for the outermost tiles. As the name implies, the readout will be analogue, with the off-detector electronics being common to the ECAL. The AHCAL has around 8,000 channels and is scheduled to be completed by September 2005. It is complemented by a "tail-catcher", consisting of 96 cm of iron instrumented with 16 layers of 5 mm × 5 cm scintillator strips, which will tag leakage and detect muons.

The digital HCAL (DHCAL) is a binary readout sampling calorimeter. The sensitive layers will be mainly resistive plate chambers (RPC) although for some of the tests, one or more layers may be replaced with gas electron multiplier (GEM) detectors. The RPC (or GEM) pads will be $1 \times 1\,\mathrm{cm}^2$, giving 400,000 channels, each reading one bit. As one of the main aims of the beam tests is to compare the performance of these HCAL options, the same absorber structure and tail catcher as for the AHCAL will be used, so as to eliminate any spurious differences which might otherwise arise. Hence, the DHCAL is also around $(1\,\mathrm{m})^3$ in volume and should be completed by summer 2006.

The first 14 layers of the ECAL are currently being exposed to a low energy electron test beam at DESY. This will be a technical commissioning run to debug the system and provide a first look at the ECAL performance. This test is expected to continue intermittently over the following six months as the rest of the ECAL is assembled and installed. The completed ECAL will then be run until July.

In September 2005, the ECAL will move to FNAL to take hadron beam data. Even without any HCAL behind it, it has been shown [4] that significant differences between hadronic shower models can be seen in the ECAL alone. These tests will continue until around November, when the AHCAL will be ready. The two detectors are then expected to take data for six months.

Around summer 2006, the DHCAL should then arrive at FNAL and again, around six months is expected for data taking with the ECAL and DHCAL together.

4 UK electronics and DAQ work

The UK has built the VME readout system for the ECAL. Upstream of the UK electronics, the signals from the silicon wafer pads are amplified and read out with the very front end (VFE) ASIC chip [5] designed by the LAL-Orsay group. The wafers and VFE chips are mounted on the VFE PCB, designed by the same group. The 60 VFE PCBs required for the full ECAL are connected to the UK electronics via mini-SCSI cables. The UK is responsible for all the readout electronics and online software downstream of the VFE PCBs.

4.1 Readout electronics

The readout system consists of six 9U VME boards which provide the control and the digitisation of the analogue signals from the VFE PCB. They also provide local buffering of data for up to 2000 events, which should be more than sufficient for each spill. One of the boards also provides trigger logic and control, with the trigger being fanned out from this central board to the other boards in the system (including itself) using point-to-point connections on a custom-built PCB which attaches to the VME J0 connectors across the crate backplane. The maximum allowable trigger latency is set by the peaking time of the shaped VFE preamplifer signal and is around 180 ns.

The boards were designed as a modification of the CMS silicon tracker Front End Driver (FED) design [6]. The Calice design required a complete replacement of the FED front end (FE), which receives the input data, with a new design. The back end (BE) and VME interface were less substantially modified. Because of this commonality, there has also been some firmware shared between the two boards, reducing the engineering effort required. An overview of the structure of the CALICE boards is shown in figure 1 together with a photograph of one of the actual boards.

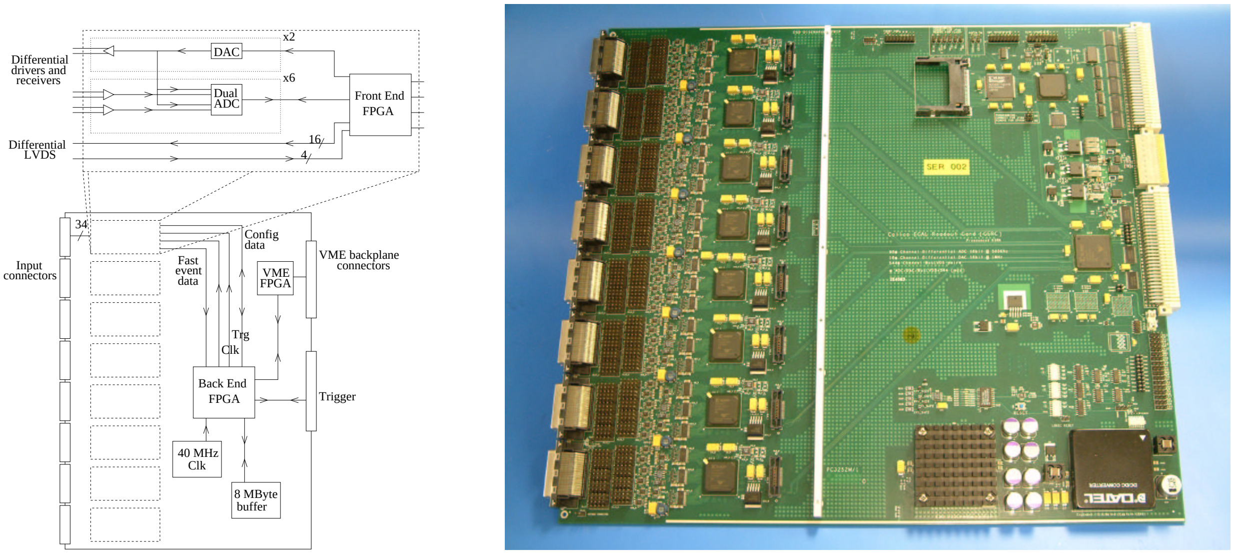

Figure 1: *Overview of the structure (left) and photograph (right) of the VME ECAL readout boards.*

Two prototype boards were fabricated by November 2003 and were thoroughly tested over the following year. These tests included a suite of stand-alone tests and calibrations using the on-board DAC. In addition, tests with the VFE PCB preproduction boards were done during early summer 2004. These involved using the DAC to calibrate the VFE PCBs, as well as using radioactive sources and cosmic rays. These tests showed that the boards were working very well [7] and only minor improvements were implemented in the design for the production versions.

Nine boards were fabricated for the production run in October 2004, of which only two were populated immediately. These two were again extensively tested before the remaining seven were released for assembly and completed in February 2005.

The first two production boards were taken to Paris for cosmic ray tests in December 2004. A system with ten layers of the ECAL, totalling over 2000 channels, was assembled in a cosmic teststand at Ecole Polytechnique. Data were taken using the UK boards over the Christmas period and a total of over 1 million events were recorded. A signal/noise of around 9 for minimum ionising particles (MIP) was seen, well above the minimum requirement of 5. Figure 2 shows an example of the very clean separation of pedestal and MIP signals, where the Landau shape is visible in the latter. These data will allow the calibration for these channels to be determined to 1%, which is sufficient for the first round of ECAL studies. Figure 3 shows an example of a cosmic event where a clear track is seen through all ten layers of the ECAL; this indicates clearly why the phrase “tracking calorimeter” is used.

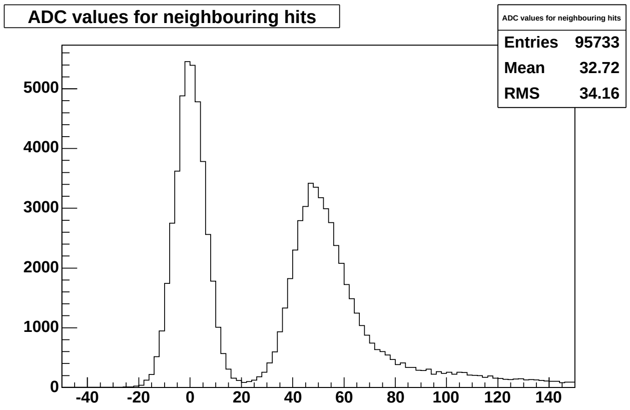

Figure 2: *Pedestal and minimum ionising signal peaks from the ECAL cosmic data taken over the last month in Paris.*

The whole ECAL system was transferred to DESY in January 2005 for the initial beam test which will continue for several months. Figure 3 also shows an example of an electron event from the test beam run.

4.2 Data acquisition software

The UK groups also provided the software data acquisition (DAQ) system for the whole of the CALICE readout.

The aim of the CALICE beam tests is to collect around 10^6 events for each configuration of beam energy, particle, type, angle of incidence, etc. This implies a complete sample of order 10^8 events. To acquire this in a reasonable time, the DAQ system should achieve an average of 100 Hz readout rate. Given the spill structure at FNAL, this means an instantaneous rate during a spill of at least 1 kHz. There will be no threshold suppression applied online as studies of pedestal stability and noise are fundamental to this work. Each event is therefore expected to be around 50 kBytes in size, giving a total raw data volume of around 5 TBytes.

The DAQ software was designed from scratch to allow a very lightweight, fast system to be

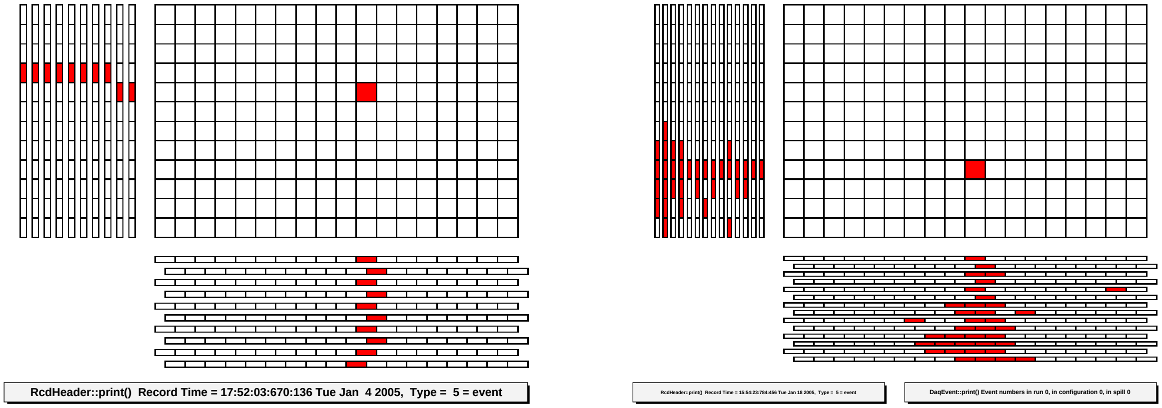

Figure 3: *Examples of events in the ECAL of cosmics (left) and electrons (right).*

developed which was tailored to the needs of Calice and so capable of achieving the high rates needed. It was implemented in C++ on Linux and only uses ROOT and the Hardware Access Library software from CERN [8].

The DAQ system has been used for all the UK board tests so far and has been running in both the cosmics tests in Paris and the electron beam at DESY. A rate of 40 Hz has been achieved so far and with further hardware, firmware and software developments, the 100 Hz requirement should be attainable.

5 UK simulation work

5.1 Hadronic shower modelling

Apart from testing the hardware concepts, one of the most important goals of the Calice test beam campaign is to gather data on the properties of showers, especially hadronic showers, in highly granular calorimeters. We therefore embarked on a program of systematic comparison between different shower packages.

The standard Monte Carlo program for simulation of the Calice calorimeters (both for the test beam, and for the full ILC detector) is `Mokka` [9], which is based on `Geant4` [10]. `Geant4` provides a toolkit approach, whereby a variety of different interaction models can be combined in different energy ranges. The `Geant4` authors provide a number of standard packages combining these models which are tailored to suit different "use cases". We have examined all those which are considered appropriate for high energy calorimetry. In addition, `Mokka` provides a facility for writing out a FORTRAN description of the detector geometry suitable for inclusion in a `Geant3` program. In this way we gain access to the physics models available in `Geant3` [11], namely `Gheisha`, `Fluka`, `Gcalor` and `Micap`. However, the old version of `Fluka` interfaced to `Geant3` is now deprecated by the authors, and the current version is not yet interfaced to `Geant4`. In order to gain access to this interesting model, we have employed a package called `Flugg` [12], which provides an interface between the `Geant4` geometry and materials, and the physics and transportation code of `Fluka` [13].

In total, seventeen different models or combinations of models have been studied [14], at different energies, for different particle species, and for two different HCAL detector technologies: scintillating tiles operated in analogue mode and RPCs operating in digital mode. Figure 4 shows some typical comparisons between these models for the case of 10 GeV π^- at normal incidence to the prototype calorimeter. In all cases the results have been normalised to the "LHEP" model which is the default in `Mokka`.

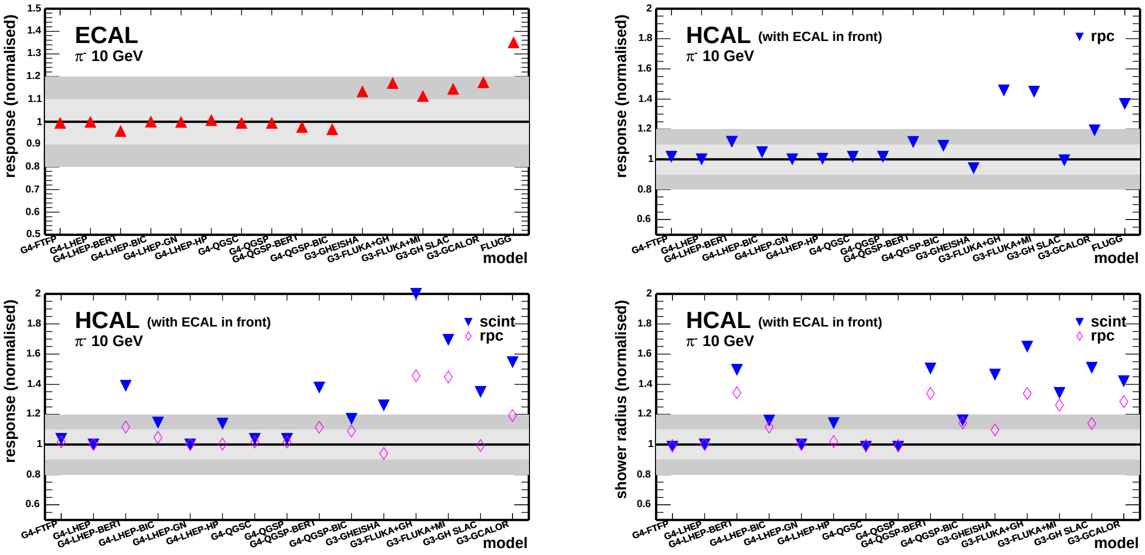

Figure 4: *Comparisons between different hadronic models for 10 GeV π^-. In each case, the results are normalised to the predictions of the LHEP model in* `Geant4`*. The upper left figure shows the response (i.e. mean energy deposited) in the* ECAL*; upper right the response (number of cells hit) in the RPC DHCAL; lower left compares the tile AHCAL response with the DHCAL; lower right compares the shower radius in the two HCALs. The shaded bands denote 10% and 20% differences.*

These studies reinforce the need for appropriate data against which to validate these models. It may well turn out that none of the models accords with data, but this will either allow us to tune models, or to assign realistic systematic uncertainties to their predictions when optimising the final detector design.

5.2 Pattern recognition

The primary motivation for a highly granular tracking calorimeter design for an ILC detector is to separate the energy depositions of different particles within hadronic jets. This permits the use of a "Particle Flow" algorithm, in which the charged particles will be measured using the tracking chambers, and the neutrals by appropriate combinations of ECAL and HCAL information. Experience from LEP, and early studies for the Tesla TDR, showed that this was the most promising way to achieve the $\sim 30\%/\sqrt{E}$ jet energy resolution demanded by linear collider physics. This resolution is not driven by the intrinsic energy resolution of either calorimeter, but by the extent to which confusion between different showers can be avoided.

Such energy flow algorithms have already been written for early ILC studies. However, these codes tend to be tied to specific simulation packages and detector geometries. In view of the need to optimise global detector designs for cost and performance, it is clearly desirable to have a flexible algorithm which can readily be adapted to new setups.

A necessary first stage is to develop a versatile and robust calorimeter reconstruction algorithm. Inspection of simple event displays in the CALICE calorimeters shows that, with the 1 cm^2 cells and fine longitudinal sampling envisaged, substructures like tracks or small clusters are commonly observed within showers. This suggests that the optimal clustering algorithm for such a calorimeter may not be a conventional "merge contiguous hits" algorithm. Within the UK we have pursued two complementary approaches to these problems. Both algorithms are interfaced to the LCIO data format [15], which is becoming the agreed standard for ILC studies.

In this way, it should be straightforward for others to use our code, and to integrate it with tools (such as tracking) developed elsewhere.

The first algorithm [16] takes a tracking approach. The calorimeter is treated in coaxial layered shells, automatically calculated for each geometry. Seed clusters are formed in the first layer of the calorimeter, and then hits in each layer travelling outwards are considered in turn. Each hit is compared with extrapolations of hits in previous layers, taking account of knowledge of the direction of the cluster from previous layers, and the best match found. If no acceptable match exists, a new cluster is seeded. In coding the algorithm, care is taken to encapsulate geometrical information and cuts in a single place. The algorithm was developed and tested on a variety of different samples – single particles, pairs of particles, and physics events such as hadronic Z^0 and W^+W^- events – simulation models and geometries. The performance seems to be quite robust. An example of the performance is given in Fig. 5. We see that photons can already be well separated from hadrons for separations above $\sim 3-5$ cm, while the separation power is a little worse for neutral hadrons. The separation power has been found to be significantly degraded if, for example, the Bertini hadronic model, which yields wider showers (seen in Fig. 4), is used.

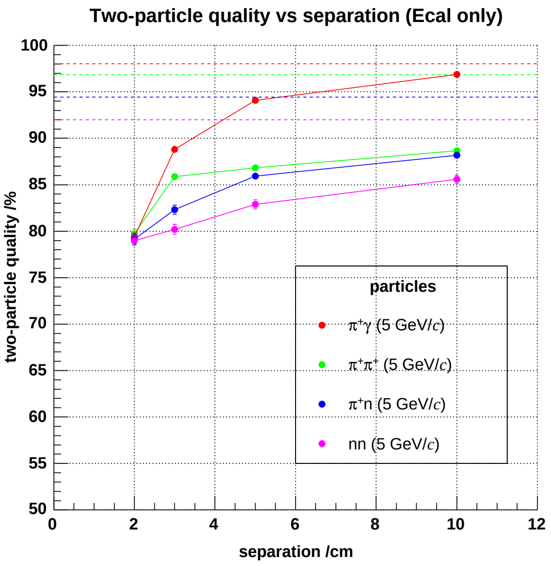

Figure 5: *Reconstruction quality (defined as the fraction of energy which has a one-to-one relation between truth and reconstruction) for various pairs of 5 GeV particles, as a function of separation at the front of the calorimeter. The dashed lines indicate the quality for single particles, i.e. the asymptotic values at infinite separation.*

The second approach to clustering [17], based on Minimal Spanning Trees (MST), is quite different. Each calorimeter hit is regarded as a node in a tree, and the MST represents the way of connecting all the nodes, with no loops, which minimises the sum of the "lengths" between nodes. Geometrical information only occurs in the metric which defines the "length", which does not have to be the geometrical distance. There are standard algorithms which efficiently compute the MST. This effectively forms the whole event into one cluster; an algorithm is then applied to form smaller clusters by cutting the tree.

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