Proposal 317 - The CALICE collaboration: calorimeter studies for a future linear collider

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1 Introduction

A future e^+e^- linear collider (LC) operating at a centre-of-mass energy in the range 500 GeV to 1 TeV is a high priority for the future of High Energy Physics. It was strongly supported by the recent HEPAP review panel in the US [1], itself based on numerous studies produced through the "Snowmass 2001" meeting [2]. UK existing and possible future involvement in various aspects of a future LC was discussed in the "Blair Report" [3].

A future linear collider would play a strong rôle in complementing the physics programme of the LHC. Research and development work towards a linear collider has been proceeding for the past decade at DESY, KEK and SLAC. Although the exact specification of a future linear collider has yet to be decided, the feasibility of such a project is demonstrated in the TESLA Technical Design Report (TDR) [4], published last year.

This proposal concerns the CALICE R&D project [5] which is aimed at providing the most effective calorimetry for an experiment at the LC. Specifically, the solution proposed for the electromagnetic calorimeter is a silicon-tungsten sandwich calorimeter with high spatial segmentation.

In this document we first outline the physics case for the LC, and the requirements this imposes on the calorimeter performance. We then introduce the CALICE R&D project and explain its objectives before describing the proposed UK contribution. We finally give lists of the resources needed and the effort, milestones and deliverables for this project.

2 Physics at a Linear Collider

The physics case for a future linear collider has been established at a series of workshops under the aegis of ECFA and DESY, and is stated in the TESLA TDR [4]. The main goals of the physics programme are summarised below:

Higgs Physics: If the Higgs boson exists, it is probable that it will have been discovered at the LHC or Tevatron before the start of the LC. Once discovered, the emphasis will be on establishing its nature. Precise measurements will be essential to establish whether the particle has the properties expected in the SM, or whether it corresponds to one of the Higgs bosons of a supersymmetric theory. However, the measurement of the properties of the Higgs boson at the hadron colliders will be relatively crude compared to what can be achieved at the LC. The measurements which the LC can perform include:

- Measurements of the Higgs boson mass and width with precisions of 0.1% (or better) and $\mathcal{O}(5\%)$, respectively.
- Precise measurements of its couplings to fermion pairs, to massive gauge bosons and to photons.
- Determination of the spin and parity of the Higgs boson.
- The Higgs boson self-coupling and hence the Higgs potential can be probed using the ZHH final state ($\rightarrow 6j$ or $\rightarrow 4j\ell^+\ell^-$).
- The Higgs-top Yukawa coupling can be measured in the final state $\mathrm{t\bar{t}H}$.
- Supersymmetric Higgs bosons may be studied in final states like $\mathrm{H^+H^-} \rightarrow \mathrm{t\bar{b}b\bar{t}}$ and $\mathrm{h^0A^0} \rightarrow 4\mathrm{b}$.

On the basis of these measurements it will be possible to establish the nature of the Higgs boson.

Supersymmetry: Supersymmetry (SUSY) is widely believed to be the most likely theory for physics beyond the Standard Model. However, if correct, the theory will need to be constrained by experiment since there are a large number of parameters and several possible scenarios for SUSY breaking. If SUSY particles exist in the sub-TeV energy range, they are likely to be discovered at the LHC where squarks and gluinos would be copiously produced. In this case, it is important to determine the properties of the SUSY particles in order to constrain the many parameters of the supersymmetric theory. The LC would fulfil a powerful complementary rôle to the LHC here, especially in determining the properties of sleptons, gauginos and the $\tilde{\mathrm{t}}$ squark. In addition to determination of the mixing parameters in the gaugino sector, precise measurements can be made of sparticle masses, widths, and branching fractions, as well as separating closely-lying mass states. The wealth of precise measurements possible at the LC will provide a powerful probe of the underlying structure of the SUSY theory.

Strong Electroweak Symmetry Breaking: If the Higgs boson is not discovered at the LHC or Tevatron, the LC should see evidence of other new physics. In the absence of the Higgs boson the cross-section for the process of longitudinal W-boson scattering, $\mathrm{W}_\mathrm{L}^+\mathrm{W}_\mathrm{L}^- \rightarrow \mathrm{W}_\mathrm{L}^+\mathrm{W}_\mathrm{L}^-$, would grow, violating quantum mechanical unitarity. To avoid unitarity violation it is required that the interaction between the vector-bosons becomes strong at energies of order 1 TeV. This would be manifested in anomalous triple or quartic gauge boson couplings. Observation of $\mathrm{W}^+\mathrm{W}^-$ and $\mathrm{Z}^0\mathrm{Z}^0$ scattering processes will be possible using the final states $\nu\overline{\nu}\mathrm{W}^+\mathrm{W}^-$ and $\nu\overline{\nu}\mathrm{Z}^0\mathrm{Z}^0$. Anomalous gauge boson couplings can be studied using similar techniques to those used at LEP, such as the reconstruction of angular distributions and correlations.

Top-quark Physics: An $\mathrm{e}^+\mathrm{e}^-$ LC provides a clean environment in which to study the properties of the top quark. In particular, the mass of the top quark is a key input in fits to high precision electroweak data. At the LC the top quark mass can be determined from a threshold scan with a precision of $\sim$ 200 MeV compared to $\sim 1 - 2$ GeV at LHC. In addition to the top quark mass, precise measurements of many of its other properties may be made at the LC.

The baseline TESLA TDR design specifies a luminosity of 3.4×10^{34} cm^{-2} s^{-1} at a centre-of-mass energy of 500 GeV. This would be upgradable to 5.8×10^{34} cm^{-2} s^{-1} at 800 GeV without replacing the linear accelerator cavities. This gives an integrated luminosity of 1 ab^{-1} in two to three years. Obviously the running strategy depends on what the LHC and LC find, but it seems that a full physics programme at a LC, such as that described above, would require a few ab^{-1} of data.

3 Calorimetry at a Linear Collider

Most of the physics processes mentioned above are characterised by multi-jet final states sometimes accompanied by charged leptons and/or missing transverse energy associated with neutrinos or the lightest supersymmetric particles. The reconstruction of the invariant mass of two or more jets will provide a powerful tool for identifying the physical process and in rejecting background. In addition, decays commonly involve a cascade through several massive states, which can be elucidated by mass reconstruction. To give just three examples: *a)* the separation of the rare but important $\mathrm{Z}^0\mathrm{H}^0\mathrm{H}^0 \rightarrow 6j$ final state from background will rely on identifying pairs of jets with the invariant masses of the Z^0 and Higgs; *b)* the identification and separation of the $\nu\overline{\nu}\mathrm{W}^+\mathrm{W}^-$ and $\nu\overline{\nu}\mathrm{Z}^0\mathrm{Z}^0$ final states will rely almost entirely on di-jet mass reconstruction; *c)* the measurement of the $\tilde{\chi}_1^\pm$ mass and the $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass difference in the process

$e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \ell^\pm \nu q\overline{q}' \tilde{\chi}_1^0$ may be achieved by measurement of the di-jet mass and energy distributions.

3.1 Lessons from LEP

Since the reconstruction of the invariant mass of two or more jets will play a major rôle in the analyses of numerous processes at the LC, a good measurement of the jet energies is of great importance. At LEP it was found that the jet energy resolution was not limited by the intrinsic momentum/energy resolution of the tracking chambers/calorimeters. Rather the resolution is limited by the ability to separate and correctly associate tracks and energy deposits in electromagnetic and hadronic calorimeters.

3.1.1 Energy Flow and Jet Energy Resolution

Measurements of jet fragmentation at LEP have given us a good understanding of the particle composition of jets (e.g., [6, 7]). On average, after the decay of short-lived particles such as Λ^0 and K_S^0, roughly 62% of the energy of jets is carried by charged particles (mainly hadrons), around 27% by photons, about 10% by long-lived neutral hadrons (n/K_L^0), and around 1.5% by neutrinos. Charged particles are most accurately measured in the tracking detectors, photons in the electromagnetic calorimeter (ECAL), and n/K_L^0 by the hadron calorimeter (HCAL). To measure the energy of the jet, information from all three detector elements has to be combined taking into account correlated energy deposits; for example a charged hadron will typically deposit energy in both calorimeters, while a neutral hadron may often start showering in the electromagnetic calorimeter. The most successful algorithms for jet reconstruction at LEP have used an *energy flow* method, in which geometrical associations between tracks and energy clusters in the calorimeter and between clusters in the electromagnetic and hadronic calorimeters are used to minimize double counting of energy. So, for example, the energy deposited in the calorimeters by a charged particle is not double counted along with the energy determined from the tracking chambers.

The ALEPH experiment at LEP obtained a jet energy resolution[1] $\Delta E/E = 60\%(1 + |\cos\theta|)/\sqrt{E}$ using such a method [8]. For comparison OPAL achieved $\Delta E/E \sim 80\%/\sqrt{E}$. Despite the OPAL lead-glass calorimeter having a better energy resolution than ALEPH's, the ALEPH calorimeter has significantly better spatial resolution, permitting better matching and separation of the various energy deposits within a jet.

3.1.2 The Rôle of Kinematic Fitting at the Linear Collider

It is worth noting that at LEP precise measurements of the W boson mass have been performed by direct reconstruction of the invariant mass of the W boson decay products. The LEP experiments did not provide particularly accurate measurements of jet energies. However, this limitation was overcome using kinematic fitting. By imposing the constraints of energy and momentum conservation, the jet energies could be determined, largely from angular information, much more accurately than by direct measurement[9].

Although kinematic fitting will undoubtedly play a significant rôle at the LC, its applicability will be more limited. As already mentioned, many of the interesting final states have missing energy. In final states with more than one unmeasured particle, there are insufficient constraints to perform a kinematic fit. Furthermore, the energy lost to initial state radiation (ISR), which is only ~ 3 GeV at LEP in W^+W^- events, becomes ~ 25 GeV at 500 GeV and ~ 50 GeV at 800 GeV. Thus at LEP the average ISR energy is much smaller than the jet energy resolution,

[1] In this and similar expressions for resolutions throughout this document, the energy E is assumed to be measured in GeV.

whereas at the LC it would be much greater. In addition, the beams at the LC will lose similar amounts of energy through beamstrahlung (radiation in the electromagnetic field of the other beam). Therefore, a significant proportion of events at the LC will not be susceptible to kinematic fitting. Consequently, good jet energy resolution becomes of paramount importance at the LC. Since jet energy resolution is mainly determined by the ability to resolve separate energy deposits in the different detector components, the calorimeters at the LC must have excellent transverse spatial resolution.

3.2 Calorimetry at the Linear Collider

The principal requirements for the electromagnetic calorimeter in a LC experiment may be summarised as follows:

- Good energy resolution for photons and electrons; needed for example for e/π separation and for the identification of $H \to \gamma\gamma$ events.
- Excellent transverse spatial resolution, in order to separate particles in jets and make energy flow measurements.
- Good longitudinal segmentation as an aid to e/π separation.
- The ability to identify non-pointing photons; for example in the gauge-mediated SUSY breaking scenario where a long-lived neutralino may decay to a photon and a stable gravitino: $\tilde{\chi}_1^0 \to \gamma\tilde{G}$.
- Excellent hermeticity.
- Good time resolution, to avoid pile-up from particles originating from other bunch crossings.
- Compact, so that the calorimetry can be placed inside the magnet coil without prodigious cost.

The preferred solution adopted for the TESLA TDR envisages a silicon-tungsten (Si-W) electromagnetic calorimeter, followed by a hadron calorimeter. Specialised calorimetry in the forward region would complete the angular coverage.

Tungsten is an attractive choice for the showering medium in the ECAL, having a very low radiation length of 3.5 mm and a small Molière radius of 9 mm. The small Molière radius allows nearby showers to be resolved. By using silicon as the detecting medium, the gaps between tungsten layers can be kept thin, so that the whole ECAL of 24 radiation lengths depth can be fitted into a thickness of about 20 cm. The granularity of the silicon readout, i.e., the size of the silicon pads, is determined by the Molière radius, which defines the transverse size of electromagnetic showers. If the pad size is significantly greater than the Molière radius the shower can only be localised to within the area of one pad and the spatial resolution is degraded. Consequently a pad size of $\sim 1\times1$ cm^2 is envisaged. The TDR design has 40 longitudinal samples and this results in 32 million diodes (i.e., channels) in total.

The HCAL would consist of 38 stainless steel plates, instrumented either with scintillator tiles, or with wire chambers or resistive plate chambers with digital readout. Both these options are still being actively investigated. A third option under consideration is a device instrumented with a mixture of the two technologies.

3.2.1 Energy Resolution

The performance of such a calorimeter has been extensively studied using Monte Carlo (MC) simulations as part of the TESLA TDR. The energy resolution of the proposed ECAL for photons has been found to be approximately given by $\Delta E/E = 1\% + 10.3\%/\sqrt{E}$ [10], leading for example to a mass resolution in $\mathrm{H}^0 \to \gamma\gamma$ of 2.1 GeV (for $M_{\mathrm{H}} = 120$ GeV). The angular resolution for photons was found to be $\Delta\theta = (8 + 68/\sqrt{E})$ mrad, corresponding to a resolution on the impact parameter at the collision point of ~ 4 cm for a 20 GeV photon [10]. Electron-pion separation, based on shower shape and matching the ECAL energy with the track momentum in the central tracker, has been estimated to yield a probability for misidentifying a pion as an electron of around 10^{-4} [10].

The case for the Si-W ECAL rests largely on its energy flow performance, which in turn leads to good jet energy reconstruction and good di-jet mass resolution. An elementary kinematic calculation shows that a jet energy resolution $\Delta E/E = \alpha/\sqrt{E}$ leads to a di-jet mass resolution of roughly $\Delta M/M = \alpha/\sqrt{E_{jj}}$ where E_{jj} is the energy of the di-jet system. A reasonable goal is to match ΔM for the W or Z bosons to their natural widths, i.e., ~ 2 GeV. Since $E_{jj} \sim 250$ GeV at the LC, this suggests that one should aim for $\alpha \sim 30\%$, i.e., more than a factor two better than that achieved by the LEP detectors. For the proposed LC detector, using an energy flow algorithm [10], an energy resolution of $\Delta E/E \sim 33\%/\sqrt{E}$ has been achieved, with scope for improvement in the algorithm, already meeting the above requirements. As an example, Figure 1 shows the reconstructed Z^0 mass distribution (from $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\overline{\mathrm{q}}$ at $E_{\mathrm{cm}} = M_Z$) determined by applying the energy flow algorithm to the jets. A mass resolution of ~ 3 GeV is achieved.

3.2.2 Physics Simulation

The impact of the quality of the electromagnetic and hadronic calorimeters on the physics results at the LC has been studied as part of the TESLA TDR. Two examples are given here. The process $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}^0\mathrm{H}^0\mathrm{H}^0$ probes the Higgs boson self-couplings and is of considerable interest in the determination of the exact nature of an observed Higgs boson. However the signal, with a corresponding cross-section of ~ 0.5 fb, needs to be separated from a large background. The invariant masses of the reconstructed di-jet pairs may be used to significantly reduce background. Having identified six jets, a useful discriminating variable is

$$D = \sqrt{(m_{12} - m_H)^2 + (m_{34} - m_H)^2 + (m_{56} - m_Z)^2}.$$

Figure 2 shows the distributions of D for signal and background for two cases: $\Delta E/E = 60\%(1 + |\cos\theta|)/\sqrt{E}$ (LEP-like) [10] and $\Delta E/E = 30\%/\sqrt{E}$ (proposed LC). The impact of improved jet resolution is apparent and is quantified in Figure 3, which shows the significance (signal/$\sqrt{\text{background}}$) as a function of the jet energy resolution parameter α, for an integrated luminosity of 1 ab^{-1} [4]. The increased significance of the signal above the background expectation in going from $\Delta E/E = 60\%/\sqrt{E}$ to $\Delta E/E = 30\%/\sqrt{E}$ is equivalent to a fourfold increase in luminosity. Given the smallness of the cross-section, a jet energy resolution of at least $\Delta E/E = 35\%/\sqrt{E}$ is required to establish the signal for an integrated luminosity of 1 ab^{-1}.

Another example of the importance of the resolution of the calorimeters at the LC is the analysis of WW scattering events which would be of great interest if no elementary Higgs boson were discovered. The identification of, and separation between, the channels $\nu\overline{\nu}\mathrm{W}^+\mathrm{W}^-$ and $\nu\overline{\nu}\mathrm{Z}^0\mathrm{Z}^0$ when the bosons decay hadronically depends crucially on di-jet mass resolution. Figure 4 shows how the separation between these two channels using the two di-jet masses in the event is improved when the jet energy resolution is changed from $\Delta E/E = 60\%/\sqrt{E}$ to $\Delta E/E = 30\%/\sqrt{E}$ [11]. The increased separation has been estimated to be equivalent to an increase of approximately 40% in luminosity.

4 The CALICE collaboration

The CALICE collaboration [5] was formed to study the issues of calorimetry for a future linear collider detector. It currently consists of 96 physicists from 17 institutes in 7 countries. The spokesperson is J.-C. Brient from LPNHE - Ecole Polytechnique and the chair of the Steering Board is R.-D. Heuer from DESY. The calorimetry sections of the TESLA TDR [4] were mainly written by members of CALICE.

The collaboration is studying both electromagnetic and hadronic calorimetry. As described above, the physics goals of a linear collider require an integrated approach to the energy measurement, so the design of the two types of calorimeter need to be closely related. The members of CALICE are roughly equally divided between three groups; one studying the silicon-tungsten ECAL, a second studying the tile scintillator HCAL while the third is studying the digital HCAL option. The UK would be interested in joining the ECAL subgroup.

The overall aim of the collaboration is to perform detailed studies of the calorimeters required for linear collider physics so that informed design choices can be made on the timescale of any likely linear collider. Specifically, one (possibly optimistic) scenario could have the linear collider beginning operations in 2012. Working backwards, this means construction of the calorimeters would need to be started around five years previous to this, in 2007. To begin construction at this time, prototyping of a likely design would need to start around two years before that, in 2005. It should also be noted that if a linear collider is to be built on this timescale, then approval would be required around 2005. Hence, the aim of the CALICE collaboration is to get to the point of knowing what should be built within the next three years, by which time the status of a linear collider may be much more certain.

At present, there are many technical uncertainties related to how to build such a calorimeter. For the Si-W ECAL, these include very basic issues such as where to put the front-end electronics. It is difficult to get sufficient cooling into the $\mathcal{O}$(mm) gaps between the tungsten plates to allow on-detector amplification; the degradation of performance as these gaps increase needs to be evaluated. The alternative is a high density of cables several metres long carrying unamplified signals that are required to have a resolution of 10 bits. This would be eased if more sophisticated energy flow algorithms reduce the required channel resolution. Other unresolved issues include the mechanical structure (the effect of dead material), fabrication of tungsten plates to the right tolerances (how well the thicknesses need to be controlled), acceptable diode yield (how many dead channels can be tolerated) and the calibration of the huge number of channels involved (how well does the calibration have to be known). In addition, the cost of the ECAL as specified in the TESLA TDR is high, estimated as 133 Meuros, with 93 Meuros of that being purely for the silicon diodes. It is clear that a serious cost-performance optimisation still needs to be done.

Many of the studies required will be done using MC simulations of various detector configurations. Most of the work involves determining the resolution of hadronic jet energies, as much of the physics depends on this quantity. This in turn depends heavily on the ability of the simulation to accurately describe hadronic interactions. However, it is thought that this is currently *not* well modelled in simulations.

A major goal of the CALICE studies is therefore to tune the simulation against real data. This requires a beam test and this forms a large part of the effort of the collaboration over the next two years. The schedule is to build a "physics prototype" of the ECAL and the two options for the HCAL and put both combinations into a test beam early in 2004. The analysis of the data is then expected to take the rest of that year.

The beam test location is not yet determined and the data may be taken at more than one laboratory. The study will need data from both electrons and hadrons at energies of the same order as the typical energy of a hadron in a LC hadronic jet, namely between 1 and 10 GeV. In addition, data from several experimental configurations will be needed; there are clearly two different HCAL options, but also the effects of particles entering the calorimeter at various angles and of material in front of the calorimeter will be studied. Overall, around 10^7 to 10^8 events are expected.

5 Proposed UK contribution

The UK groups propose to join the CALICE collaboration to work on the silicon-tungsten ECAL. We have discussed with the collaboration potential places where we could contribute and we propose to work in two areas:

- The beam test ECAL readout electronics and overall data acquisition seem to be a good match in terms of the UK expertise and effort and this area is not currently covered by other collaborators. We detail below the ECAL part of the physics prototype and what the UK intends to contribute. The same electronics should also be able to read out the tile HCAL and we propose to produce extra boards to do this.

- In addition, the UK groups have a strong interest and relevant experience in the software studies to develop energy flow algorithms, including the use of novel techniques such as neural networks. We would also like to consider the cost/performance optimisation of the design. This activity would lead directly to analysis of the test beam data when it becomes available in 2004.

The UK groups consider this work to be a commitment for the next three years. Joining the collaboration would not necessarily tie the UK into a calorimeter project for the linear collider. However, if this project is successful and the UK wishes to remain involved in the long term, then we would clearly be very well placed to play a major role in a linear collider calorimeter. The UK groups involved have all expressed an interest in readout electronics for the long term (in addition to several other potential areas), so if this did lead on to a future involvement, this project would put us in a very strong position.

5.1 The ECAL physics prototype

The prototype ECAL will consist of 30 layers of silicon diodes interleaved with 30 layers of tungsten, which has a radiation length $X_0 = 3.5$ mm. The tungsten layers will have varying thickness; the first 10 layers will be 1.4 mm thick (corresponding to $0.4X_0$ each), the next 10 will be 2.8 mm thick ($0.8X_0$) and the last 10 will be 4.2 mm ($1.2X_0$). The total thickness is therefore $24X_0$. The physical size of the active area will be $18 \times 18 \times 18$ cm^3.

Each detection layer comprises a 3×3 array of silicon diode wafers, with each diode being 1×1 cm^2 and each wafer containing a 6×6 array of diodes. Every diode needs to be read out and so corresponds to a channel. Hence, each wafer contains 36 channels, each layer contains $36 \times 9 = 324$ channels and the whole prototype is $324 \times 30 = 9720$ channels.

The three silicon wafers in a row in each layer will be mounted on PCBs that route the diode signals (without amplification) to the very front end (VFE) chips which provide amplification and shaping. Each layer therefore consists of three such PCBs which are mechanically connected but electrically independent.

The VFE chip will handle 18 channels and will provide a sample-and-hold for each signal on an external trigger for each channel. It will have a single gain amplifier and will multiplex the signals from the 18 channels onto a single output line at up to 1 MHz. The VFE chip will also accept a calibration signal which is used to inject a pulse at the chip input.

The diodes, VFE chips, wafer PCBs and their power supplies, as well as the trigger and its logic, will be provided by non-UK groups, while the UK groups propose that they provide all the readout electronics downstream and the data acquisition system to read it out.

5.2 The proposed readout electronics

The proposed system is relatively straightforward and is not expected to require any major technical development. Given the relatively short timescale, simplicity and robustness were emphasised over high performance. A brief description is given below, with further details available in [12].

An overview of the physics prototype and the proposed UK readout electronics is shown in Figure 5. The proposed readout system communicates with the PCB-mounted silicon wafers via twisted pair cables, attached to each of 15 VME boards mounted in a single 6U crate. All of the necessary readout electronics is contained on these boards. The system will run triggered and read out each event before allowing the next trigger to occur. This will be controlled by a single VME trigger handling board which distributes the trigger across the backplane. No data reduction is done in hardware, so all 9720 channels are read out for each trigger.

A dedicated board will be needed to test the readout boards. This will produce signals equivalent to those expected from the ECAL and use the same cables as the final system. This allows the whole readout electronics chain to be tested.

5.2.1 The readout board

A conceptual layout of the readout board is shown in Figure 6. It consists of line drivers and receivers for the cable lines, ADC's to digitise the analogue signals and one or more FPGAs to control the board and the VME interface. It also contains DACs for VFE calibration.

Each readout board must digitise the signals from six silicon wafer PCBs. The board takes in six twisted-pair cables, one from each of the wafer PCBs, through its front panel. These cables carry control and timing signals to the VFE chips and the analogue signals from the VFE chips. This number of cables corresponds to two ECAL layers, or $6 \times 6 = 36$ multiplexed VFE chip outputs, which will be digitised using 16-bit ADCs.

Following receipt of a trigger over the J2 backplane, the FPGA generates a pre-defined readout sequence of signals for the VFE chips; namely the sample-and-hold, followed by the multiplex shift register control signals and strobes for the ADCs. All the timing for these signals is configurable through VME to give maximum flexibility.

Each board receives data from 648 channels, which is 648×2 bytes $= 1296$ bytes and buffers these data within the FPGA until read out via VME. Each event consists of 9720 channels $\times$ 2 bytes $= 19440$ bytes or 19 kbytes.

The readout board can also generate a calibration sequence, which is similar to the readout sequence but first sets a voltage level on a 16-bit DAC and strobes the calibration circuit in the VFE chips before initiating a readout sequence as above. The channels being calibrated can be chosen using configurable calibration select lines.

5.2.2 The trigger board

The trigger module must receive a trigger from an external source and output this trigger to all readout boards via the J2 backplane bus. It must generate a veto which stops any further trigger being output until it is cleared via VME.

In addition, the trigger board at the prototype-testing stage will allow stand-alone generation of triggers from a front panel push-button and from VME. It will output the veto signal to all the readout boards via the J2 backplane bus. It will have VME registers for status, command and external input enables. It will also have a stand-alone clock oscillator (probably at 60 MHz).

To allow maximum flexibility for integration with the HCAL readout the final trigger board will also allow for outputs of the clock to all readout boards via J2 backplane bus, for a front panel external clock and veto/input, and will provide multiple front panel outputs for clock, trigger and veto signals.

5.2.3 The test board

The test board will connect to a readout board via a cable connected to the readout board front panel, exactly as for the standard input. The test board will output differential analogue signals from a 16-bit DAC to simulate the output from VFE chips up to the 1 MHz VFE multiplex rate. A total of 6×6 differential analogue outputs are required to test a complete readout board.

The test module should also receive and check the analogue calibration voltages, sample-and-hold signals, 1 MHz multiplexing clock input, calibration pulses and calibration select signals.

5.3 The proposed data acquisition system

The data acquisition system will need to read out all subsystems in the beam test, not just the ECAL, so that the data from both calorimeters can be analysed together.

The physics prototype version of the tile scintillator will consist of up to 1200 channels with a pulse shaping time that is comparable to that of the ECAL VFE chip. It is therefore plausible that the tile scintillator HCAL could use the same readout boards as the ECAL, hopefully with minimal modifications as the timing of all control signals is software configurable. Three extra readout boards are included in the proposal to cover this option.

The digital HCAL will have 38 instrumented layers with around 10000 channels per layer, each producing a single bit of data. This system will require a completely different readout and the UK groups do not propose to provide this.

In addition, there will need to be readout for the beam monitoring and trigger systems. This is to a large extent unspecified, but it is known that it will be provided by non-UK groups. To cover these as well as the HCAL readout, a system containing two VME crates will be necessary and we request a second VME crate for this purpose.

Including the ECAL, the total event size is expected to be around 30 kBytes per event for the tile HCAL option and up to 80 kBytes per event for the digital HCAL, depending on the level of zero suppression implemented. This will take at least 1 ms to read over VME and so will limit the event rate to a maximum of around 1 kHz. As a high data rate is not a major design requirement for this project, a throughput rate of around 100 Hz would be acceptable. This gives a data sample of $\mathcal{O}$(Tbyte) in total.

The software for the data acquisition will be adapted from existing systems where possible. Members of the UK groups have provided online code for the MINOS experiment and heavy reuse of this is expected.

5.4 Proposed simulation studies

The optimization of the design of the LC electromagnetic and hadronic calorimeters in terms of cost and physics performance is of great importance, particularly given the relatively high cost of the proposed calorimeters. The final design will be optimized using MC simulation. These MC studies will enable a quantitative comparison of the performance of the energy flow algorithm for different detector configurations. However, before relying on these studies it is necessary to verify the accuracy of MC simulation. Using data recorded in the CALICE test beam it will be possible either to verify or to improve the MC implementation of electromagnetic and hadronic showers. Of particular interest is the response of the CALICE calorimeters to hadronic showers, since it is well known that the GEANT3 simulation of hadronic showers is not perfect. The impact of these uncertainties on energy flow, and therefore physics performance, is a question that is relevant to the design of the final LC calorimeters. In addition, since the CALICE (and future LC) MC programs are being written using GEANT4, it is important to verify the simulation of electromagnetic showers.

The CALICE test beam programme will provide high statistics samples of electromagnetic and hadronic showers. Given the high granularity of the CALICE calorimeters, it should be possible to test the MC simulation to high precision. Members of the UK groups have considerable experience in the area of MC simulation, having been involved in simulation work at LEP. Two of the UK institutes have already installed GEANT4 and the existing calorimeter simulation code and have used this code for studies of the event sizes and data rates in the prototype.

Having worked on the simulation of CALICE, the UK groups would be well placed to provide significant input to the optimization of the design of the calorimetry for the LC.

6 Deliverables, costs, timescale, effort

6.1 Deliverables

There are only a few deliverables for this project. The UK will commit to providing:

- A readout system for the ECAL physics prototype.
- A data acquisition system for the whole physics prototype.
- Better understanding of and improvements to the simulation.
- Improvements to the calorimeter design.

6.2 Costs

In addition to the purpose built boards described above, the system needs commercially available infrastructure, namely cables, PCI/VME interface cards, a high-end PC, some disk storage and VME crates. Therefore, the estimated cost of the readout electronics and data acquisition system is:

- Non-recurring design costs; for all electronics = £2k.
- Readout boards; £2800 per board $\times$ 22 boards = £62k.
- Trigger board (estimated); £1200 per board $\times$ 3 boards = £4k.
- Test board; £2900 per board = £3k.
- Cables (estimated); £30 per cable $\times$ 100 cables = £3k.
- PC and disk; £4k for the PC, £8k for 1.4 Tbytes of disk = £12k.
- VME interfaces; £4k for PCI-VME interface, £3k for VME extender = £7k.
- 6U VME crate and power supplies; £5k per crate $\times$ 2 crates = £10k.

All values given are in FY02/03 prices and include VAT, so the total cost of the equipment for the project is therefore FY02/03 £103k.

6.3 Timescale

Table 1 shows the milestones for the readout electronics. The system needs to be ready for a beam test in early 2004. It therefore needs to be completed by the end of 2003. Fabrication, testing and data acquisition software development of the full system is likely to require around 6 months, which sets the end of the prototype phase to be mid-2003. Therefore, the time from approval to mid-2002 will be used to complete the specification of the electronics. The rest of 2002 will be used for designing the boards. Prototype fabrication will take place early in 2003 and prototype testing will take the rest of the first half of 2003.

Hence, prototype costs will be incurred in FY02/03 while production will occur in FY03/04. The prototype costs will be for some of the infrastructure (PC, the PCI-VME interface, one VME crate and a few cables), two readout boards and the test board, giving a total of £23k in FY02/03. The remaining infrastructure and board production costs, totalling FY02/03 £80k, will all be incurred in FY03/04.

Milestone	Date of completion
Readout electronics specification completed	End June 2002
Prototype readout board design completed	End December 2002
Test readout board design completed	End February 2003
Prototype readout board layout and fabrication completed	End February 2003
Test board layout and fabrication completed	End April 2003
Prototype readout board testing completed	End June 2003
Production readout board design completed	End July 2003
Trigger board design completed	End August 2003
Production readout board layout and fabrication completed	End September 2003
Trigger board layout and fabrication completed	End October 2003
Production readout board testing completed	End December 2003
Trigger board testing completed	End December 2003

Table 1: Milestones for the readout electronics.

6.4 Engineering effort

The readout board will require around 18 months of engineering effort in total; 12 months for the board design and 6 for the FPGA firmware. We estimate that 12 months of engineering effort will be required for the design of the test and trigger boards. In addition, 1 month will be needed for layout and fabrication of each of the prototype readout board, the production readout board, the test board and the trigger board. This is a total of 34 months.

We propose to provide 18 months for the readout board design effort, including the FPGA design, and the test and trigger board design effort from University staff. The rest of the effort would then be provided by RAL TD, with 12 months needed for the rest of the board designs and 4 months for the layout and fabrication of all the boards. This effort will be divided approximately equally between FY02/03 and FY03/04, which are the two FYs in which the system is being produced.

6.5 Travel

UK travel for CALICE-UK meetings and LC-UK meetings is estimated to be £10k per year. For travel outside the UK, general CALICE meetings are held approximately every two months. With four UK people attending on average, this will cost around £24k per year. CALICE collaboration meetings are also held during the EFCA/DESY [13] and International LC [14] workshops. The former are held every six months and the series is expected to be continued after next spring. The latter are held every 18 months. With two UK people attending on average, this will cost £8k per year. This gives a total travel cost of £42k per year.

The beam test itself will require major extra travel funds for FY03/04. However, as the most appropriate location and duration of the beam test are currently under investigation, the following is an estimate. Assuming, for example, a two month (60 days) beam test with five people at DESY during this period, then the cost would be around £6k per person, or £30k in all. In addition, it is likely there will be costs associated with the setup and running of the test beam itself, for which the UK share will be up to £10k.

7 Summary

An important design goal for the calorimetry at the LC is a jet energy resolution of $\Delta E/E \sim 30\%/\sqrt{E}$. At this value the typical uncertainty on reconstructed W/Z boson masses due to jet energy uncertainty is approximately equal to Γ_W. To achieve this level of performance energy flow techniques will be vital. At LEP it was found that the performance of the energy flow algorithm depends crucially on the ability to match tracks with the corresponding calorimetric clusters from the same particle and the ability to separate energy deposits from different particles. Consequently good transverse spatial resolution is of great importance. A silicon-tungsten electromagnetic calorimeter with silicon pad size of 1×1 cm^2 represents the most promising technical possibility for achieving these goals so far considered. MC studies of the current design for the LC calorimetry yield a jet energy resolution of $\Delta E/E \sim 30\%/\sqrt{E}$, a factor of two better than achieved at LEP. This improvement in jet energy resolution has a large impact on the physics capabilities of the LC, significantly improving the separation between signal and background in important physics channels and as a result significantly reducing the integrated luminosity (i.e., the running time) required to make a discovery.

The CALICE collaboration aims to resolve many of the technical issues associated with building such a calorimeter. The UK groups have an opportunity to join this collaboration in an area for which significant effort is needed and in which the UK groups have a strong long-term interest.

References

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[14] For the next meeting, see http://lcws2002.korea.ac.kr/

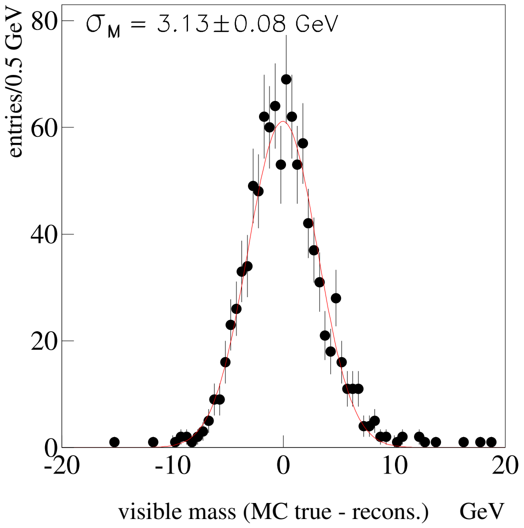

Figure 1: *Mass resolution for hadronic* Z^0 *decays at rest.*

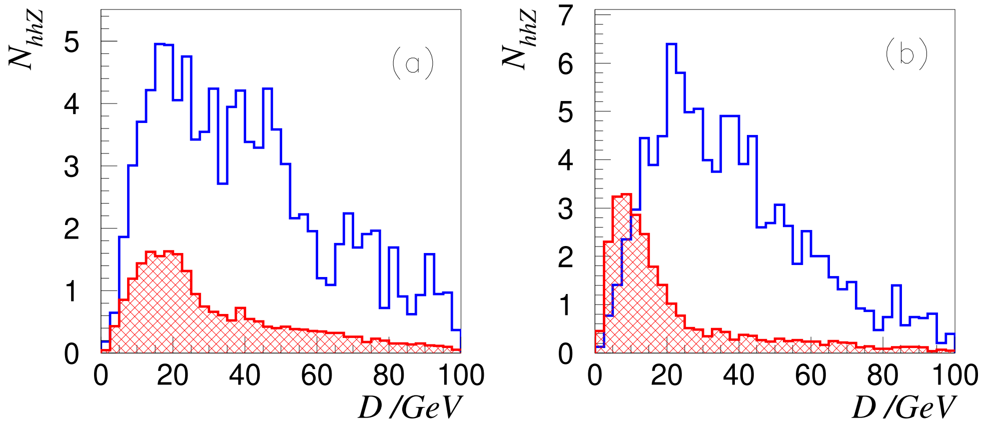

Figure 2: *Distributions of the discriminating variable* D *for* $Z^0H^0H^0 \to 6j$ *signal (hashed) and background (clear), for two values of jet energy resolution: a)* $\Delta E/E = 60\%(1+|\cos\theta|)/\sqrt{E}$ *(LEP-like); b)* $\Delta E/E = 30\%/\sqrt{E}$.

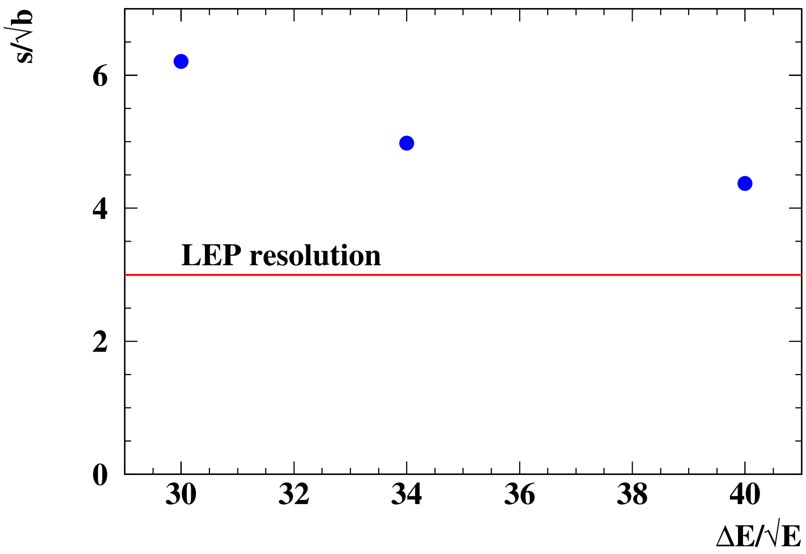

Figure 3: Signal/$\sqrt{\text{background}}$ *for the separation of* $\mathrm{Z^0H^0H^0} \to 6j$ *using 1* ab^{-1} *of data, as a function of the jet energy resolution parameter* α *(in %), where* $\Delta E/E = \alpha/\sqrt{E}$*. The horizontal line indicates the LEP-like case* $\Delta E/E = 60\%(1 + |\cos\theta|)/\sqrt{E}$*.*

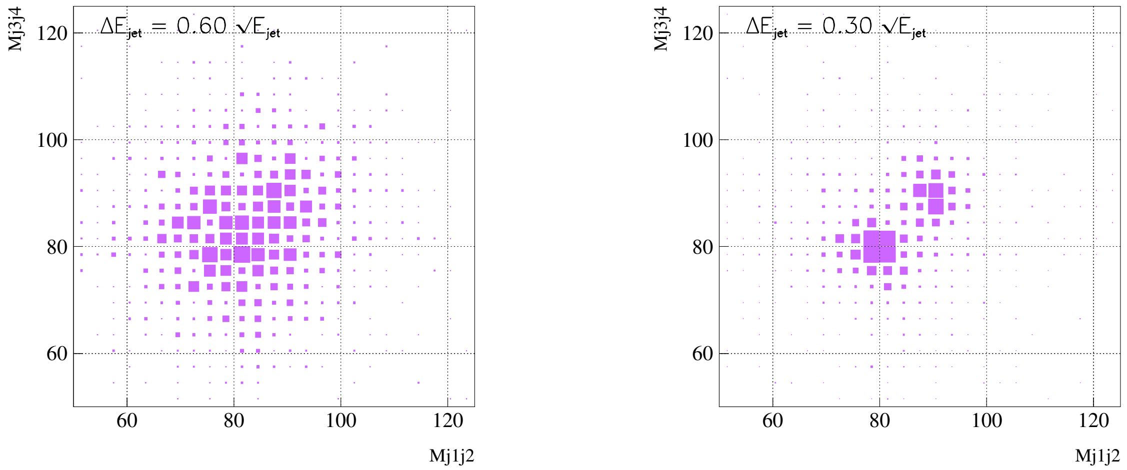

Figure 4: *Reconstructed di-jet masses for* $\nu\overline{\nu}\mathrm{W^+W^-} \to 4j$ *and* $\nu\overline{\nu}\mathrm{Z^0Z^0} \to 4j$ *for two values of jet energy resolution: a)* $\Delta E/E = 60\%/\sqrt{E}$*; b)* $\Delta E/E = 30\%/\sqrt{E}$*.*

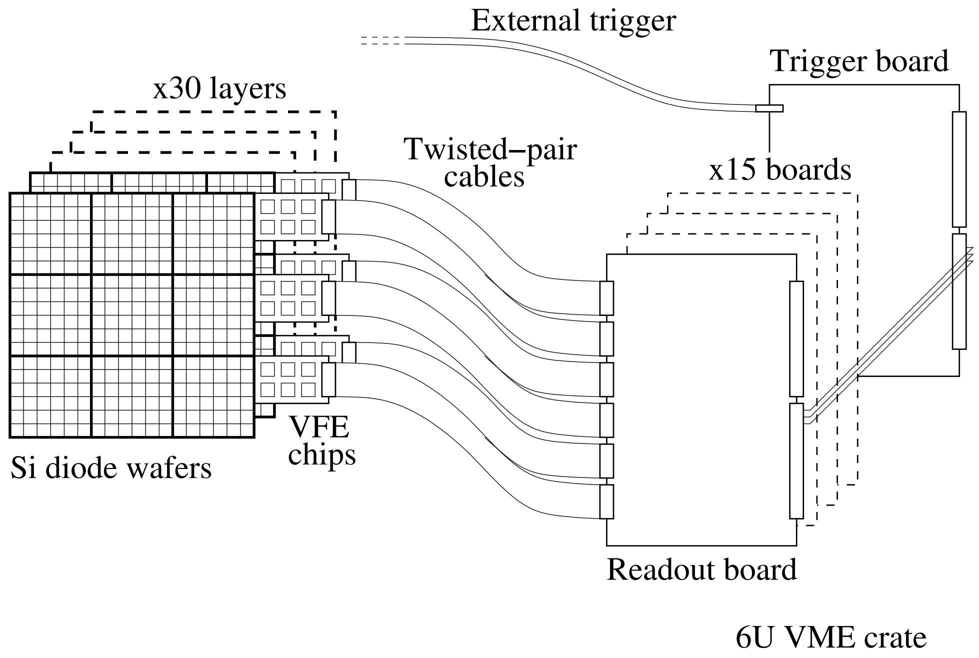

Figure 5: *Overview of the ECAL physics prototype and readout electronics.*

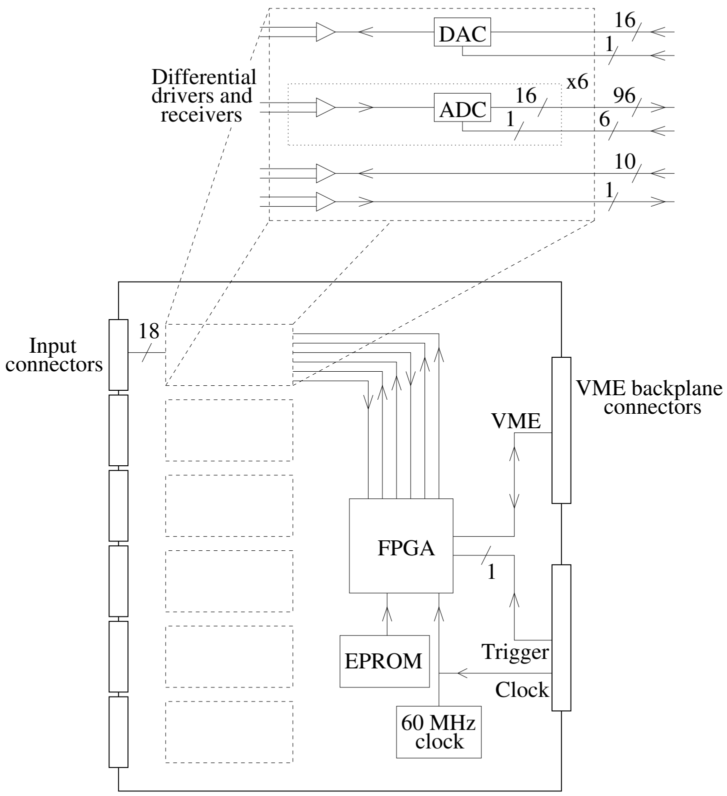

Figure 6: *Conceptual layout of the readout board. For clarity, the set of signals to only one of the six input connectors is shown.*

A Appendix

Tables detailing individual effort and costs are given below.

A.1 Individual effort

The fractions of effort for each person involved are shown in Table 2. The lines labelled "New RA" are posts which are being requested in the current rolling grant submission. We request funding for them from the PPRP as a contingency against them not being awarded through the rolling grant.

Institute and Tasks	Name	Funding	FY02/03	FY03/04	FY04/05
Birmingham	C. M. Hawkes	HEFCE	0.1	0.1	0.1
Data acquisition	N. K. Watson	HEFCE	0.4	0.3	0.0
Simulation studies	New RA	PPARC	0.1	0.2	0.2
Cambridge	C. G. Ainsley	Fellow	0.5	0.5	0.5
Online software	M. A. Thomson	HEFCE	0.1	0.2	0.2
Simulation studies	D. R. Ward	HEFCE	0.2	0.3	0.3
Imperial College	D. A. Bowerman	Fellow	0.1	0.2	0.2
Readout board	W. Cameron	PPARC	0.2	0.2	0.1
Data acquisition	P. D. Dauncey	HEFCE	0.2	0.2	0.2
	D. R. Price	PPARC	0.2	0.2	0.0
	O. Zorba	PPARC	0.2	0.2	0.0
	New RA	PPARC	0.0	0.3	0.3
UCL	J. M. Butterworth	HEFCE	0.1	0.1	0.1
Trigger board	D. J. Miller	HEFCE	0.1	0.1	0.1
Test board	M. Postranecky	PPARC	0.1	0.1	0.0
	M. Warren	PPARC	0.1	0.1	0.0
	New RA	PPARC	0.0	0.0	0.5
Manchester	R. J. Barlow	HEFCE	0.1	0.1	0.2
Readout board	I. P. Duerdoth	HEFCE	0.1	0.1	0.1
Test software	N. M. Malden	PPARC	0.1	0.1	0.1
Simulation studies	D. Mercer	HEFCE	0.1	0.1	0.0
	R. J. Thompson	HEFCE	0.0	0.0	0.1
RAL TD	Engineering	PPARC	0.7	0.7	0.0

Table 2: FTE effort per year. All University groups will be involved in analysis of the beam test data, so this task is not listed explicitly here.

A.2 Cost breakdown

The funds requested from the PPRP for each of the three FYs covered by this proposal are shown in Table 3. New RAs are costed at £35k (outside London) or £39k (within London) per FTE. As stated above, the RA costs are requested only as contingency against the posts not being awarded in the next rolling grants round.

	FY02/03	FY03/04	FY04/05	Total
Equipment	23	80	0	103
New RA Effort	3	19	39	61
Total Cost to PPRP	26	99	39	**164**

Table 3: Requested funding from PPRP per year. Units are FY02/03 £k.

The total cost to PPARC for each of the three FYs covered by this proposal are shown in Table 4. This cost is independent of the source of funding of the "New RA" posts. Other University PPARC personnel are costed using their actual salaries, including all overheads. RAL TD effort is costed at £68k per FTE.

	FY02/03	FY03/04	FY04/05	Total
Equipment	23	80	0	103
University PPARC New RA Effort	3	19	39	61
University PPARC Other Effort	53	53	11	117
RAL TD Effort	48	48	0	96
Travel and beam time expenses	42	82	42	166
Total Cost to PPARC	169	282	92	**543**

Table 4: Total estimated PPARC cost per year. Units are FY02/03 £k.