Proposal to join the CALICE collaboration

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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-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]. A future linear collider would play a strong rôle in complementing the physics program 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) [2], published in the past year.

This proposal concerns the CALICE R&D project [3] which is aimed at providing the most effective calorimetry for an experiment at the LC. Specifically, the solution proposed for the electro-magnetic 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 in detail 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 [2]. 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 $t\bar{t}H$.
- Supersymmetric Higgs bosons may be studied in final states like $H^+H^- \rightarrow t\bar{b}b\bar{t}$ and $h^0A^0 \rightarrow 4b$.

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 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. 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, $\mathrm{W}^+_\mathrm{L}\mathrm{W}^-_\mathrm{L} \to \mathrm{W}^+_\mathrm{L}\mathrm{W}^-_\mathrm{L}$, would grow, violating quantum mechanical unitarity. To avoid unitarity violation it is required that the interactions 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 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 with a precision of ~ 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.

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 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 $\mathrm{Z}^0\mathrm{H}^0\mathrm{H}^0 \to 6j$ 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 $\tilde{\chi}^\pm_1$ mass and the $\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1$ mass difference in the process $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}^-_1\tilde{\chi}^+_1 \to \ell^\pm\nu\mathrm{q}\overline{\mathrm{q}}'\tilde{\chi}^0_1$ 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., [5, 6]). On average, after the decay of short-lived particles such as Λ^0 and K^0_S, 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^0_L), 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^0_L 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 obtains a jet energy resolution[1] $\Delta E/E = 60\%(1+|\cos\theta|)/\sqrt{E}$ using such a method [7]. For comparison OPAL achieves $\Delta E/E \sim 80\%/\sqrt{E}$. 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 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[4].

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, 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:

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

- Good energy resolution for photons and electrons; needed for example for e/π separation and for the identification of H$\rightarrow \gamma\gamma$ 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: $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{\mathrm{G}}$.
- Excellent hermeticity.
- Good time resolution, to avoid pile-up.
- 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 thickness 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 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 simulations as part of the TESLA TDR. The energy resolution of the proposed ECAL for photons has been found to be approximately given by $\Delta E/E = 1\% + 10.3\%/\sqrt{E}$ [8], leading for example to a mass resolution in $\mathrm{H}^0 \rightarrow \gamma\gamma$ 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 $\sim$ 4 cm for a 20 GeV photon [8]. 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} [8].

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 $\Delta E = \alpha\sqrt{E}$ 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., $\sim$ 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 [8], 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 $e^+e^- \to q\overline{q}$ at $E_{cm} = M_Z$) 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 TESLA TDR. Two examples are given here. The process $e^+e^- \to Z^0H^0H^0$ 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 reconstructed 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: $\Delta E = 0.3\sqrt{E}$ (proposed LC) and $\Delta E = 0.6(1+|\cos\theta|)\sqrt{E}$ (LEP-like) [8]. 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} [2]. The increased significance of the signal above the background expectation in going from $\Delta E = 0.6\sqrt{E}$ to $\Delta E = 0.3\sqrt{E}$ is equivalent to a fourfold increase in luminosity. Given the smallness of the cross-section, a jet energy resolution of a least $\Delta E = 0.35\sqrt{E}$ 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 great interest if no elementary Higgs boson is discovered. The identification of, and separation between, the channels $\nu\overline{\nu}W^+W^-$ and $\nu\overline{\nu}Z^0Z^0$ 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 $\Delta E = 0.6\sqrt{E}$ to $\Delta E = 0.3\sqrt{E}$ [9]. The increased separation has been estimated to be equivalent to an increase of approximately 40% in luminosity.

4 The CALICE collaboration

The CALICE collaboration [3] 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. Although there is some US and Korean involvement, most of the institutes are from Europe and Russia and so the collaboration is mainly focussed on the TESLA collider; indeed, the calorimetry sections of the TESLA TDR [2] were mainly written by members of CALICE.

The collaboration is studying both electromagnetic (ECAL) and hadronic (HCAL) 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 would 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, i.e., in 2007. To begin construction at this time, prototyping of a likely design would need to start around two years before that, i.e., 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 CALICE collaboration aim 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 less uncertain.

At present, there are many technical uncertainties on how to build such a calorimeter. For the 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. However, the alternative is a high density of cables several metres long carrying unamplified signals which are supposed to have a resolution of 10 bits. Other unresolved issues include the mechanical structure, fabrication of tungsten plates to the right tolerences and the calibration of the huge number of channels involved. In addition, the cost of the ECAL as specified in the TESLA TDR is extremely high. The total is 133 euros, with XXX euros of that being purely for the silicon diodes. It is clear that a serious cost-performance optimisation still needs to be done.

Most of the studies required will be done using simulations of various detector configurations. However, much of the physics requires an excellent resolution for the energies of hadronic jets. The studies to achieve this in turn depend 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 at present.

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 of the HCAL and put both combinations into a test beam early in 2004. The analysis of the data is expected to then take the rest of the year.

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. This is a hardware contribution and so requires equipment funds and some engineering effort.

- In addition, the UK groups have a very strong interest in the software studies to develop energy flow algorithms, including the use of novel techniques such as neural networks, and also to consider cost/performance optimisation of the design. This activity would lead directly to analysis of the test beam data when it becomes available in 2004. Although it has no cost implications for the PPRP it would involve PPARC-funded personnel and computing equipment.

The UK groups consider this work as a committment 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 was successful and the UK wished to remain involved for 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, so it 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 mounted between 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 wafer containing a 6×6 array of diodes. Each 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 PCB's 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 PCB's which are mechanically connected but electrically independent.

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

5.2 The proposed readout electronics

The proposed system is relatively simple and is not anticipated to require any major technical development. A brief description is given below, with further details available in [10].

The proposed system readout system communicates with the (PCB mounted) silicon wafers via twisted pair ribbon 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 would run triggered and read out each event before allowing the next trigger to occur. This would be controlled by a single VME trigger handling board which distributes the trigger across the backplane. No data reduction is done in hardware, thus all 9720 channels are read out for each trigger.

The VFE chip will handle 18 channels and will provide a sample-and-hold 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.

A conceptual layout of the readout board is shown in Fig. 5. Each readout board must digitise the signals from six silicon wafer PCB's. The board takes in six twisted-pair ribbon cables from the wafer PCB's through its front panel. This corresponds to $6 \times 6 = 36$ multiplexed VFE chip outputs which will be digitised using 16-bit ADC's.

Each board receives data from 648 channels, which is 648×2 bytes $= 1296$ bytes and stores these data until read out via the VME backplane. Each event consists of 9720 channels $\times$ 2 bytes $= 19440$ bytes or 19 kbytes. 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 high data rate is not the major design driver for this system, a throughput rate of a few hundred Hz would also be acceptable.

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 progress on defining the readout for either of the two HCAL options is unfortunately slow and neither is as well specified as the ECAL. The prototype version of the tile scintillator will consist of 800–1200 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. Three extra readout boards are included in the proposal to cover this option. Although the total data volume of the digital HCAL would be similar to that of the ECAL itself, at approx. 10^4 1-bit channels per instrumented layer, it would 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 also to a large extent unspecified, but it is known it will be provided by non-UK groups. To cover these as well as the HCAL readout, a system containing two VME crates would be necessary.

6 Deliverables, costs, timescale, effort

Tables detailing individual effort, a total of the costs and the milestones can be found in the Appendix.

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.
- Analysis results on the data taken with the physics prototype.

6.2 Costs

We assume that we will build 2 prototypes of the readout boards and for production, we need 15 readout boards plus 3 for the tile HCAL plus 2 spares. The trigger board will need at most 1 prototype board and, for production, 2 boards plus 1 spare. The PCB connector test board will be produced during prototyping and no production of this is needed. In addition to the purpose built boards, the system also needs commercially available infrastructure, namely, two PCI/VME interface cards, a high-end PC and some storage disk. Therefore, the cost of the readout electronics and data acquisition system is:

- Readout boards; £1850 per board × 22 boards = £41k.
- Trigger board; £1000 per board × 4 boards = £4k.
- Test board; £2000 per board = £2k.
- Cables; £10 per cable × 90 cables = £1k.
- PC and VME interfaces; £12k total = £12k.
- Disk; £1000 per 100 GByte disk × 10 disks = £10k.

- 6U VME crate and power supplies; £10k per crate × 2 crates = £20k.

All values given are in FY02/03 prices, so the total cost of the equipment for the project is therefore FY02/03 £90k.

6.3 Timescale

The system needs to be ready for a beam test in early 2004. It therefore needs to be completed before 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, from the time of approval to the end 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, one VME interface, one crate, one disk and a few cables) and some of each of the boards, giving a total of £26k in FY02/03. The remaining infrastructure and board production costs, totalling £64k, will all be incurred in FY03/04.

6.4 Effort

The two boards will take a full time equivalent engineer for the time of approval up until the system is complete, i.e., end 2003. This is likely to be around 18 months, half in FY02/03 and half in FY03/04. This gives a total engineering requirement of 0.75SY for FY02/03 and 0.75SY for FY03/04, making a total of 1.5SY.

This effort will be provided by the Universities or RAL.??? RAL TD cost is £68k per year per FTE.

We also hope to obtain around one FTE of a rolling grant PDRA probably from fractions of existing posts spread over the five groups concerned, which would therefore also be PPARC funded.

6.5 Travel

UK travel for CALICE-UK meetings and LC-UK meetings will be around £10k per year. Outside the UK, general CALICE meetings may cost around £25k per year and the ECFA/DESY workshops would be around £15k per year. This gives a total of £50k 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 for all. In addition, it is possible there will be costs associated with the setup and running of the test beam itself, for which the UK share might be around £10k.

7 Summary

An important design goal for the calorimetry at the LC is a jet energy resolution of $\Delta E \sim 0.3\sqrt{E}$. 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. Monte Carlo studies of the current design for the LC calorimetry yield a jet energy resolution of $\Delta E \sim 0.3\sqrt{E}$, 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 techincal 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.

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[10] C. M. Hawkes et al., *Specification of the readout electronics for the CALICE beam test*, `http://www.hep.ph.ic.ac.uk/~dauncey/lc/specification.ps`

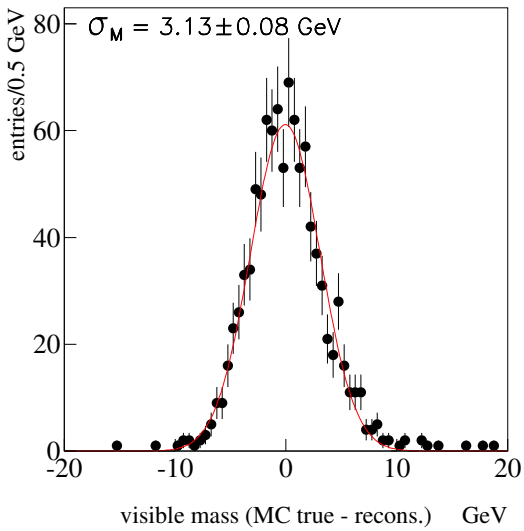

Figure 1: *Mass resolution for hadronic* Z^0 *decays at rest.*

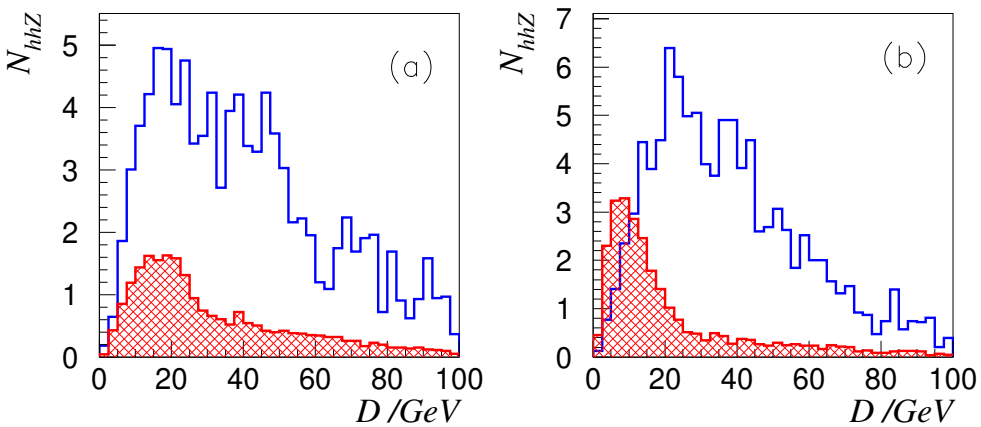

Figure 2: *Distributions of the discriminating variable* D *for* $Z^0H^0H^0 \to 6j$ *signal and background, for two values of jet energy resolution: a)* $\Delta E = 0.6(1+|\cos\theta|)\sqrt{E}$ *(LEP-like); b)* $\Delta E = 0.3\sqrt{E}$.

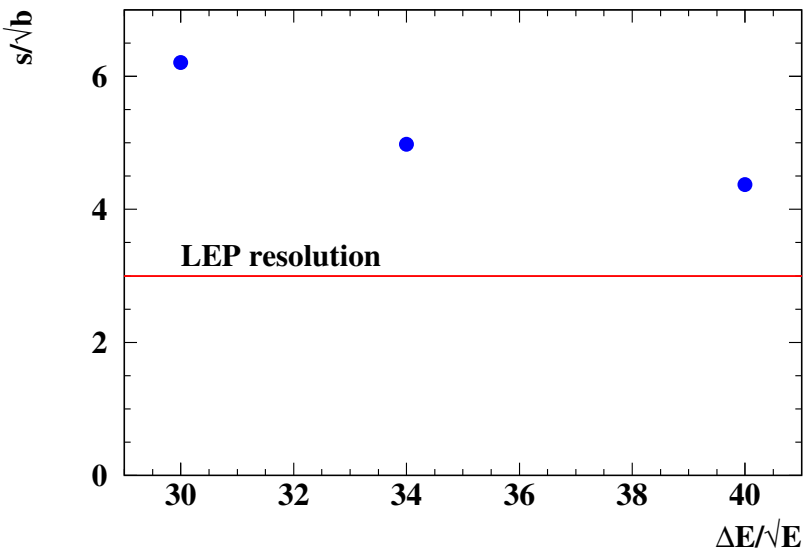

Figure 3: Signal/$\sqrt{\text{background}}$ *for the separation of* $\mathrm{Z^0H^0H^0} \to 6j$ *using 1* ab^{-1} *of data, as a function of the jet energy resolution parameter* α *(in %), where* $\Delta E = \alpha\sqrt{E}$*. The horizontal line indicates the LEP-like case* $\Delta E = 0.6(1 + |\cos\theta|)\sqrt{E}$*.*

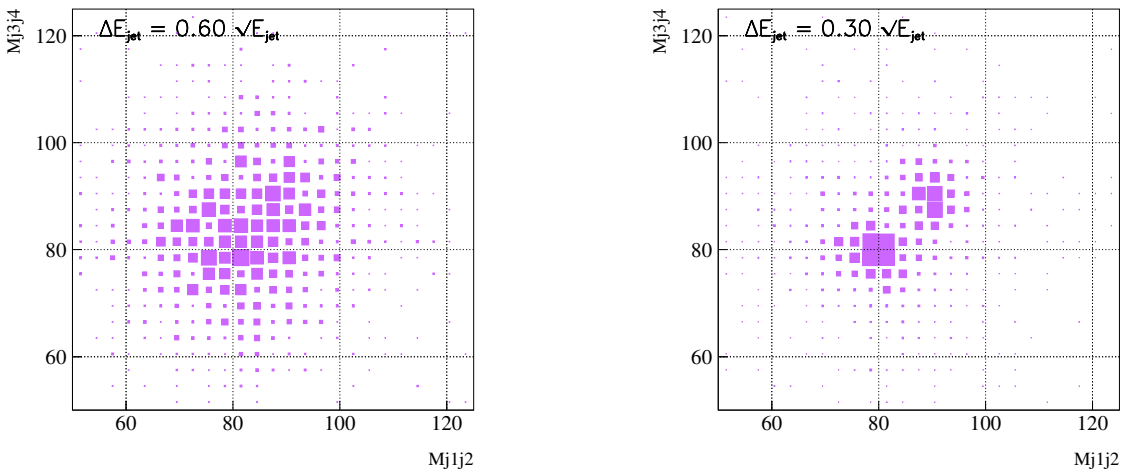

Figure 4: *Reconstructed di-jet masses for* $\nu\overline{\nu}\mathrm{W^+W^-} \to 4j$ *and* $\nu\overline{\nu}\mathrm{Z^0Z^0} \to 4j$ *for two values of jet energy resolution: a)* $\Delta E = 0.6\sqrt{E}$*; b)* $\Delta E = 0.3\sqrt{E}$*.*

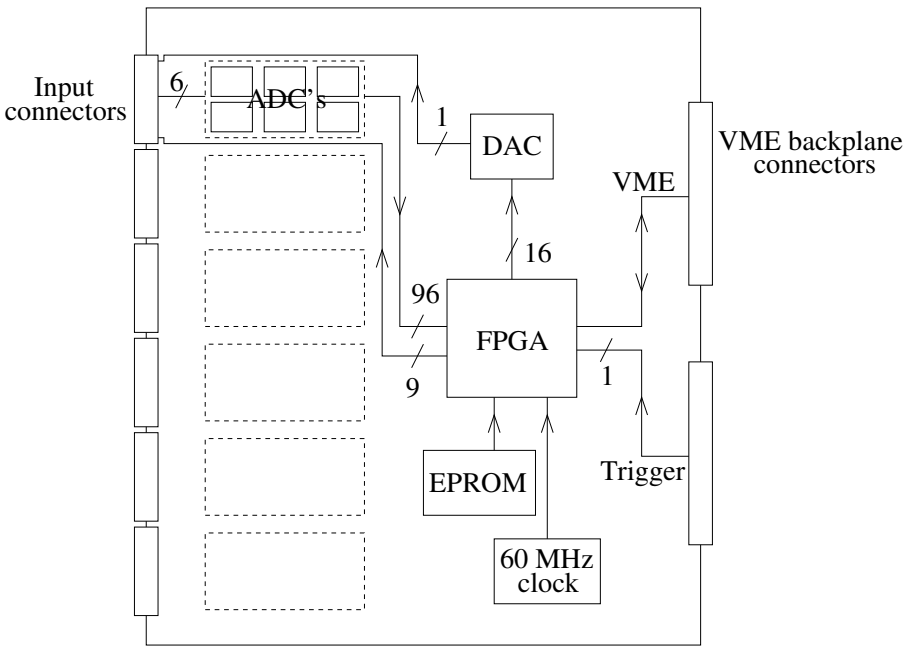

Figure 5: Conceptual layout of the readout board. For clarity, the set of signals to only one of the six input connectors is shown.

A Appendix

Institute	Name	Funding	FY02/03	FY03/04	FY04/05
Birmingham	C. M. Hawkes	HEFCE	0.2	0.2	0.2
	S. J. Hillier	PPARC	0.2	0.2	0.2
	R. J. Staley	PPARC	0.2	0.2	0.2
	N. K. Watson	Fellow	0.2	0.2	0.0
Cambridge	C. Ainsley	PPARC	0.2	0.2	0.2
	M. A. Thomson	HEFCE	0.2	0.2	0.2
	D. R. Ward	HEFCE	0.2	0.2	0.2
Imperial	P. D. Dauncey	HEFCE	0.2	0.2	0.2
	O. Zorba	PPARC	0.2	0.2	0.0
UCL	J. M. Butterworth	HEFCE	0.2	0.2	0.2
	M. Postranecky	PPARC	0.2	0.2	0.0
	M. Warren	PPARC	0.2	0.2	0.0
Manchester	R. J. Barlow	HEFCE	0.2	0.2	0.2
	I. P. Duerdoth	HEFCE	0.2	0.2	0.2
	N. M. Malden	PPARC	0.2	0.2	0.2
	D. Mercer	PPARC	0.2	0.2	0.0
	R. J. Thompson	HEFCE	0.2	0.2	0.2
Totals		non-PPARC	1.8	1.8	1.8
	Engineering	PPARC	1.0	1.0	0.0
	Other	PPARC	0.6	0.6	0.6

Table 1: FTE effort per year.

	FY02/03	FY03/04	FY04/05	Total
Equipment	26	64	0	90
RAL TD Engineering Effort	0	0	0	0
University PPARC Engineering Effort	60	60	0	120
University PPARC Other Effort	30	30	30	90
Travel and beam time expenses	50	90	50	190
Total	166	244	80	**490**

Table 2: Cost per year. Units are FY02/03 £k.

Milestone	Date of completion
Prototype readout and trigger board design completed	December 2002
Prototype readout and trigger board fabrication completed	February 2003
Prototype readout and trigger board testing completed	May 2003
Production readout and trigger board design completed	June 2003
Production readout and trigger board fabrication completed	August 2003
Production readout and trigger board testing completed	December 2003

Table 3: Milestones for the readout electronics.