REPORT TO THE PPC

A LEADING UK INVOLVEMENT IN THE FUTURE LINEAR COLLIDER

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1. EXECUTIVE SUMMARY

This report addresses the case for PPARC involvement in the future e^+e^- linear collider (LC) operating in the energy range 0.5-1 TeV. We identify opportunities for UK leadership in both the detector and the accelerator, identify a strategy for the period 2002-4 and place this in the context of a longer-term LC programme.

The UK continues to be a leader in LEP, HERA, and LHC experiments. We have a first rank reputation in particle physics based largely on these collaborations. The LC will be the premier particle physics machine in its class. For the future of UK particle physics it is absolutely essential that we are involved at a level commensurate with our expertise and reputation. This will require an eventual investment at the level of £35M to the detector.

The TESLA Technical Design Report will be published on March 23rd 2001 with a possible funding decision on the time-scale of two years and an internationally coordinated programme of detector R&D has already begun. The other LC proposals are also well advanced. The UK needs to get involved now in detector R&D to secure its position in future collaborations and the needs over the next two years are identified at the level of £3.5M.

Participation in the LC will require contributing to the accelerator costs, either directly to a common fund or by contributions in kind to the machine. This report identifies how a stake in the machine at the level of 10% can be achieved by taking a lead in the beam delivery system or the damping rings. A strategy for the next two years that will position us to do this is identified and it requires support at the level of £5.5M.

2. INTRODUCTION

The physics case for the LC has been well documented [1,2] and worldwide workshops [3] have been addressing detailed proposals for realising such a facility. The UK has been playing an active and significant role in these workshops by convening several working groups and leading key physics studies, detailed detector simulations and ongoing detector R&D programmes [4].

The LHC promises a wealth of data, after 2005, on the electroweak symmetry-breaking sector (around 1 TeV) of the standard model and UK physicists will be leaders in analysing this data and understanding its implications. There is, however, a firm consensus that the LHC alone will not be sufficient to explore physics fully at this critical energy scale. A lepton collider will be essential to complete the picture and make precision measurements and the machine closest to realisation in this context is the LC. The need to budget for the LC in the PPARC roadmap has been recognised for some time and the programme was included in the Long Term Science Review (LTSR) [5].

UK participation in the LC physics programme is essential to maintaining our international standing in particle physics, however it will necessarily involve contributing to the costs of building the machine. Indeed, it is likely that the level of influence in the LC management structure will be related to the contributions of the participants, so the UK needs to start planning now towards how to pay its share. One way would be to write a cheque to a common fund and then concentrate on building the detector. Another would be to invest at home in accelerator technology, expertise and UK industry and then make the contribution in kind. The second strategy is clearly advantageous and is intrinsically attractive because many exciting challenges lie in the accelerator design. For the UK to play a full part, a revitalising of the UK accelerator physics programme will be required. This document proposes a strategy for this process and builds on a Statement of Interest submitted to the PPESP last year [6], where potential UK participation in the beam delivery system (BDS) and accelerator damping rings (DR) was outlined.

We propose a balanced programme of physics studies, detector R&D and accelerator R&D. The strategy has a longer-term view, encompassing both the LC and CLIC, and will position the UK as leaders at the e^+e^- energy frontier for the foreseeable future. The next two years are a window of opportunity to achieve this. Unlike other future longer-term physics programmes, the LC construction period could be imminent, with important decisions to be taken in the period covered by this report. This challenging time-scale is something in our favour because our international colleagues are keen to support us, especially now that we have already shown that we can contribute.

3. PHYSICS CASE

Despite the success of the Standard Model of particle physics, it does not answer some of our biggest questions: What is the origin of particle masses? What determines their masses and other properties? Why are there three generations of fermion? What is the dark matter that constitutes the majority of the material in the universe? Are the forces of nature unified? Can gravity be understood at the quantum level? Does this involve extra space-time dimensions?

These questions can only be answered by physics beyond the Standard Model (BSM). There are many theoretical models, but ultimately the answer can only come from experiment.

The combined precision electroweak results from recent experiments lead us to believe that this new physics will become apparent at energy scales of a few hundred GeV. Particle physics therefore stands at the threshold of a new era in which we will move from measuring the properties of the Standard Model to understanding what determines these properties. The LHC and a LC should, together, provide the answers to many of these questions.

The first goal of the LC is to search for BSM physics, taking advantage of the unique discovery potential of lepton colliders, in particular for particles with only electroweak couplings. The second is to make precise measurements of all new particles and effects found by the LHC and LC. With the possibilities of combining e^+e^- running with e^-e^-, $e^-\gamma$ and $\gamma\gamma$, polarizing the beams, and varying the collision energy, the LC is an essential tool in understanding the nature of whatever is discovered.

In almost all BSM scenarios the LHC, or perhaps the Tevatron before it, will discover at least one new particle or discover deviations from the Standard Model. However, many of these effects can be hard to interpret without the detailed measurements the LC would provide. For example, the discovery of the Higgs boson may be through the observation of a clear resonance in the two-photon mass spectrum, but only by producing that resonance in other processes and measuring its width, spin-parity and couplings to a wide range of particles could we truly tell whether it is the Higgs boson of the Standard Model.

The main advantages of the LC are:

- Signal processes typically have a similar rate to their background, whereas the LHC will have to dig most signals out of backgrounds that are many orders of magnitude larger.
- The initial state is clean, simple and well understood and most processes proceed via electroweak interactions, which can be calculated with very high precision.
- The beams may be polarized, enabling enhancement of some signals and measurement of additional couplings.
- The collider energy can be easily varied to optimize or separate different signals.
- The clean experimental environment allows highly hermetic detectors and allows high resolution detectors to be put close to the interaction point giving excellent tagging of quark flavour in the final state.
- Event rates are low enough that hardware triggers are not needed and event pile-up is negligible.

A high degree of electron beam polarization has been demonstrated by SLC and is a central component of the LC programme. As we discuss below, the exciting possibility of a polarized positron source is also now being considered. This would buy a further factor of two increase in effective luminosity for most physics processes, and would give an extra diagnostic tool in separating out different signals.

Of course it is impossible to predict what physics lies beyond the Standard Model and hence what the LHC may discover. However, current precision electroweak data point strongly to a light Higgs boson, in the 113-210 GeV range either with or without supersymmetry. If there is not a light Higgs boson then there have to be new interactions that contrive to reproduce its effect at current energies, but which become apparent at higher energies, typically through WW scattering.

To cover this range of possibilities, we have examined three scenarios:

1. The LHC discovers a light Higgs boson and nothing else.
2. The LHC discovers one or more Higgs bosons and several other new particles.
3. The LHC disfavours a light Higgs boson and discovers new high energy interactions.

In all three, the LC has the potential to make additional discoveries and would make crucial measurements, yielding an understanding of the discoveries made.

A fourth, less likely, possibility is that there is a light Higgs boson, but it escapes detection at the LHC and Tevatron because it has non-standard decay modes. Even then the LC could discover it and measure its mass and couplings.

In addition, whatever the physics scenario, crucial understanding will come from the LC's ability to make ultra-precise measurements of the Standard Model particles, particularly the top quark and W and Z bosons, which far exceeds the precision of the LHC or existing experiments.

Although by no means exhaustive, we briefly discuss some of the most important physics measurements that could be made. In addition to these planned channels, it is important to stress that a LC experiment would be built to be as sensitive as possible to unexpected channels and completely new physics.

The Higgs Boson

If there is a fundamental Higgs boson, it is likely that it will first be seen by the LHC or Tevatron, but only one or at most two combinations of production cross section times decay branching fraction will be measured there. It is imperative to establish that the observed particle is the Higgs boson by measuring its full set of couplings, as well as its spin-parity and CP quantum numbers. This is especially true in scenario 1, in which its properties might give the only information about BSM physics.

The LC is able to trigger on all Higgs events, through the recoil of the Z boson in the process $e^+e^- \to ZH$. This means that absolute measurements of branching fractions can be made, including to invisible products, which could potentially be the dark matter particles. At least seven decay modes can be measured well: $b\bar{b}$, $c\bar{c}$, WW, ZZ, $\tau^+\tau^-$, $\gamma\gamma$ and gluon-gluon. The last two are particularly important, as they proceed only via quantum loops and give information about all particles that couple to the Higgs boson, even those too massive to be produced directly. The production cross section from WW fusion ($e^+e^- \to \nu_e\bar{\nu}_e H$) can be well measured and, by combining with the branching fraction to WW, offers a unique possibility to measure the total Higgs decay width. The top quark coupling to the Higgs boson, the largest coupling in the Standard Model, could be measured from the process $e^+e^- \to t\bar{t}H$ to about 5%. The Higgs boson's self-coupling can also be measured, through $e^+e^- \to ZHH$.

All these studies are essential to prove that what has been discovered is in fact a Higgs boson.

Supersymmetry

Supersymmetry (SUSY) relates the properties of fermions and bosons and is an essential component of all current attempts to unify gravity with the other forces. It predicts that every Standard Model particle be accompanied by a 'sparticle' partner. SUSY must be broken, but to fit in with the high energy unification of the forces, the breaking must be small enough that the sparticles do not have masses above a few hundred GeV.

If this is the case, the strongly interacting sparticles, the squarks and gluinos, will almost certainly have been found by the LHC or Tevatron. Some other sparticles may also have been inferred from the cascade decays of the squarks and gluinos, but only the LC will be able to make a systematic study of all the sparticles within its kinematic reach. In particular, sleptons, sneutrinos, neutralinos and charginos are all cleanly produced in electroweak interactions and can be very precisely measured. In many scenarios of SUSY-breaking several sparticles are almost degenerate in mass and mix with one another. Using the beam polarization and the ability to scan in energy, the LC will be able to separate these states and measure their couplings individually.

From the slepton decay spectrum at the LC, it is possible to make an extremely precise measurement of the mass of the lightest neutralino, which would contribute to the dark matter of the universe. Furthermore, since the LHC is only able to precisely measure mass differences between sparticles, the LC is able to add value to the LHC's measurements by setting the absolute scale.

In addition to "conventional" SUSY models, the LC offers the flexibility to explore a variety of other scenarios. *R*-parity could be violated, in which case sparticles can be produced singly as well as in pairs and the lightest sparticle can decay, violating lepton- and/or baryon-number conservation. Additional space-time dimensions could become apparent at accessible energies, giving rise to new resonances, new interactions or events in which gravitons carry off missing momentum.

The Top Quark

Since the top quark is the heaviest Standard Model particle, it is sensitive to new physics associated with the origin of mass. Precise measurements of its properties are therefore needed. Running the LC at the top quark threshold will allow its mass to be measured with an experimental precision of about 50 MeV and its width to a few per cent. Running at higher energy will give its vector and axial couplings to photons, W and Z bosons and gluons all to 5-10%.

The W Boson

The properties of the W boson are very precisely predicted by the Standard Model so precise measurements would give a clear indication of BSM physics, or constraints on it. Anomalous triple-gauge boson couplings can be measured with fraction of a per mille precision allowing the Standard Model loop corrections to be measured for the first time. These are again sensitive to new high energy interactions and particles too heavy to be produced directly.

Lower Energy Running

A short run at the Z pole and W threshold would give about 100 times the LEP statistics with higher polarization and quark flavour tagging performance than SLD. This would enable most current Standard Model measurements to be improved by at least a factor of five; a factor of ten for $\sin^2\theta_W$. The W mass could be measured to about 6 MeV. These would allow the indirect measurement of the Higgs mass to reach a precision of about 5%. Comparison of the indirect and direct measurements constitutes a stringent test of the Standard Model and gives more constraints on the structure of new physics and physics at energy scales well above any collider. This is important in all scenarios, but especially in 1 and 3.

A LC in the 0.2-1 TeV range is ideally suited to complement the discovery potential of the LHC, both by making discoveries of its own and by exploiting whatever has been discovered by either machine. Its real strength is its ability to make very precise measurements of the properties of new particles and interactions.

For the longer term, once we have understood the physics revealed by this next generation LC, a lepton collider working at centre-of-mass energies of 1-5 TeV would be very attractive. In particular, in scenario 3, in which the LHC or LC observes new high energy interactions in WW scattering (where the Ws are radiated off the incoming quarks or electrons), the full structure of these interactions may not be apparent until energies of 2-3 TeV. In many supersymmetric scenarios, some sparticle masses are a TeV or higher. If higher dimensions open up at the TeV scale, a wealth of new phenomena will be revealed there.

LC technology will therefore be central to the particle physics programme for the next twenty to thirty years.

4. PHYSICS STUDIES

The UK has been playing a significant role in the international workshop series over the last few years, benefiting greatly from prominent leadership in the worldwide organising committees and by supplying the chair of the ECFA/DESY workshop. This core commitment to LC physics has resulted in the UK convening key physics and detector working groups, including those for SUSY, QCD, Machine-Detector Interface, Simulation, Alternative New Physics, Vertexing, and Generators. Many of the headline results for both physics and detector performance that have been included in the TESLA TDR [1] and the US White Paper [2] have prominent contributions from UK physicists.

The excellent precision on mass and coupling measurements obtainable at the LC means that many of the present limiting errors are theoretical in origin. There is consequently a need to promote activity in this area so that the theoretical errors may be matched to the experimental ones by the time the LC is producing mature results. With this in mind, new initiatives (such as the international *Loopverein*) have been set up to address detailed theoretical issues. Additional support for RAs to work on LC-specific phenomenology would provide a high return for a comparably modest investment.

In the next two years, the international workshops will continue and the UK should enhance its already significant role in these activities. This will involve attending the continuing ECFA/DESY meetings, occasional attendance at the US workshops and, approximately every two years, the LCWS series of conferences. Recent expenditure on these aspects of the LC programme has amounted to approximately £12k per year. Some of this was obtained from other sources including *ad hoc* external grants and benefiting from overlaps with other duties (*e.g.* LEP duties at CERN). The decline of LEP activity and the desirability of increasing our presence in the physics working groups, especially to encourage young UK theorists to play a central role, means that the funding for these activities should be significantly increased.

5. DETECTOR DEVELOPMENT

Traditionally the UK has always been prominent in the general-purpose detectors at the major accelerators and as a result has led the extraction of key physics results and the management of the physics programmes. If the UK is to maintain its standing in particle physics, this leadership should be maintained at the LC and, to achieve this, a detector R&D programme is now required. A detailed detector proposal including costing has been developed for the TESLA TDR and UK physicists were central to this process. By way of introduction we present first a brief overview of this detector, emphasizing a few key points, we then identify some areas where the UK may now opt to concentrate its efforts. Such a detector would be appropriate for all the LC proposals. Additional possibilities exist for the second interaction region, where a detector optimised for $\gamma\gamma$ or lower-energy mode may be required; these are not discussed in detail here.

The TESLA Detector

To meet the challenges in precision set by the LC physics programme, the detector has to be excellent in every regard. One global measure of excellence is energy-flow, which is the combination of tracking and calorimetery to optimise the overall reconstruction of jets. Unprecedented energy-flow resolution of $0.3/\sqrt{E}$ (GeV), a factor 2 better than that achieved for the LEP detectors, will be required for many key measurements such as the Higgs tri-linear self-coupling or for distinguishing between hadronic WW or ZZ final states in the event that strong couplings are at the heart of electroweak symmetry breaking. This energy-flow performance drives the need for very high performance calorimetry and excellent global tracking performance $\delta\left(p_T^{-1}\right) < 5\cdot 10^{-5}$ GeV^{-1}c.

Excellent granularity and resolution are required for the calorimeter both for the global energy-flow performance and for sensitivity to specific physics channels. For instance, in the case of the gauge-mediated SUSY scenario, it may be necessary to reconstruct photons with impact parameters of only a few cm, whereas in the case of minimal supergravity in the large $\tan\beta$ scenario, multi-τ final states can be frequently expected, requiring excellent τ-finding efficiency. A highly segmented electromagnetic calorimeter (ECAL) can help in both these cases through detailed spatial reconstruction of electromagnetic clusters both for non-pointing single photons and for reconstruction of π^0 s in single-prong τ decays. A particularly interesting option for the ECAL is a silicon tungsten sampling calorimeter (SiW).

Very good hermeticity is central to many important physics channels. Detection of missing energy, *e.g.* that arising from neutrinos in jets, from neutralinos in SUSY or from energy escaping to the extra-dimensional bulk, requires good detector hermeticity at all angles. The low angle region is especially important for SUSY when the mass difference between the sparticles and the LSP is small. This need for high hermeticity extends also to the many interesting channels that have six or more fermions in the final state, where at least one of these fermions will be going in the forward direction. Tagging of electrons at low angles is crucial for vetoing or measuring $\gamma\gamma$ events. The TESLA detector can provide a calorimetric measurement at polar angles down to 27.5 mrad and a fast luminosity monitor, sensitive down to 4.6 mrad, can provide an electron tag/veto.

Good vertex detector performance is at the heart of an enormous range of physics investigations. In addition to providing unprecedented flavour identification performance, for both *b* and *c*-quarks, the detector will provide the necessary two-track separation for tracks in very dense jets, improve τ identification efficiency and provide both stand-alone pattern recognition and accurate space-points, essential to the global tracking performance. The proposed vertex detector has 5 layers, with radii of 1.55 cm, 2.4 cm, 3.6 cm, 4.8 cm and 6.0 cm. The current baseline design, developed by UK groups, uses an 800 million channel CCD detector, with pixel granularity of 20 μm$\times$20 μm. Alternative technologies are active pixel detectors (APS) or CMOS pixels.

A TPC is foreseen as the principal tracking device. The average single hit resolution is about 150 μm and a resolution of 1mm is expected along the *z* direction. The proposed TESLA TPC has 200 pad rows, allowing excellent pattern recognition for V^0 decays and kinks, the former being important to the energy-flow performance. The advantage of a gaseous detector, in addition to the *dE/dx* capability, is that it minimises multiple scattering, which is important to the energy-flow because the average track momentum in a 500 GeV CMS hadronic event is around 2 GeV. In order to achieve the overall excellent global tracking performance, the TPC and VXD are supplemented by silicon detectors in the barrel region and silicon disks in the forward region, which are also vital for the effective energy spectrum (beamstrahlung) measurement. A possible set of straw chambers between the TPC and the ECAL would improve the momentum resolution and act as a pre-shower detector after the TPC endplate.

Opportunities for the UK

The wide experience of the UK experimental community puts us in a good position to contribute to any aspect of the detector. Last year the DESY-Physics Review Committee set up an R&D Review Process [11] that will provide international peer review of proposals related to the LC detector and aid movement towards a more formal collaboration in the next few years. Historically, UK leadership in the physics has been secured as a result of early participation in the experimental programmes. We should aim to continue this successful strategy by contributing now to the development of detectors for the LC. A balanced programme should include both tracking and calorimetry and we now address these possibilities in turn.

Vertex Detector: The UK already has a clear lead in vertex detector design and has set the standard in both the ECFA/DESY and the US workshops. This has been the achievement of the UK LC Flavour Identification (LCFI) collaboration and we recommend that this work be supported as a high priority over the period 2002-4 and beyond. The LCFI group comprises Bristol, Glasgow, Lancaster, Liverpool, Oxford and RAL [5]. It aims to develop a prototype vertex detector for the LC and has produced a detailed proposal for the next 4 years R&D effort [10].

In addition to physics studies [8], the LCFI group has focussed on three areas: the material budget for the detector, the read-out, and radiation damage issues. As mentioned above, most of the tracks in LC hadronic events have momentum around 2 GeV, which means that multiple scattering makes an important contribution to impact parameter measurement errors. The LCFI group has investigated the possibility of using unsupported CCDs, fixed at their ends and kept under tension. Tests have indicated that a modest tension is enough to ensure that such a detector has a mechanical stability of better than a few μm. The SLD upgrade detector thickness was 0.4% of a radiation length, the current world record. The original LC goal was 0.12% and the unsupported silicon goal is 0.06%, a phenomenal improvement. The long bunch trains of a LC and the small bunch spacing will require a much faster read-out than for the SLD detector. For a NLC-like accelerator design, a read-out frequency of 50 MHz would be sufficient. TESLA has much longer bunch trains and it would be necessary to read out each column of the CCD separately [9]. The proposed design builds on the very successful VXD2 and VXD3 CCD detectors of the SLD experiment at SLAC. This challenging work has received international recognition and features prominently in the TESLA TDR [1], [9].

The LCFI proposal [10] should be funded as part of a longer-term coherent LC R&D strategy. For the purposes of this report, their funding request for the period 2002-4 is £1.4 M. The cost of building the CCD VXD for TESLA is currently estimated as £1.5-£2M after the R&D phase.

High performance calorimetry: A very interesting option would be for the UK to play a major part in the development of SiW calorimetry. Following experience at BaBar and LEP, one could envisage taking on the ECAL endcap which, in addition to being a key component for essentially all the physics channels, fits nicely with the low-angle calorimetry and the beam delivery system (BDS) issues. The TDR quotes a cost for the entire SiW ECAL of £82.9M, about 40% of this is attributable to the endcaps, so we estimate a production cost of £33M. The cost of the ECAL means that its performance will need to be fully justified in advance of production, by extensive prototyping and test-beam work. To start this programme off, an R&D budget should be allocated to support a community of the same approximate size as LCFI but with an allowance for the fact that the costs are dominated by the high intrinsic costs of the Si and W, so prototypes will be expensive. We estimate that £1.5M would be a reasonable start for the period 2002-4, with the expectation that R&D costs would rise rapidly after that period.

Low angle region: The low angle region is central to LC physics and the design of this "mask" region is of direct relevance to the VXD. In addition, the challenge of building high-performance calorimeters at low angles, in a region filled with machine and beam diagnostics components and irradiated by beam-related backgrounds, is linked directly with the design of the BDS. The TDR quotes a production cost for the low angle calorimeters of £0.3M. An R&D budget of order £0.3M over the period 2002-4 would give this programme a good start and allow aspects such as radiation hardness to be explored in advance of detailed design proposals post-2004.

Others: The field is clearly open for the UK to participate in the design, prototyping and construction of any of the detector components, although it should be mentioned that our international colleagues are already aligning themselves towards favoured options. The Si trackers are clearly something that could be taken up directly by the LHC UK tracking groups, the TPC also presents interesting challenges, which will be familiar to the HERA UK groups. To allow for this range of possibilities and to enable speculative new initiatives, we propose that an additional £0.3M should be made available for LC R&D in responsive mode.

The nature of the LC also means that there is no hard dividing line between the detector and the BDS, so beam-line components such as fast-feedback kickers, the Compton polarimeter and nanometre beam profile monitors could be considered part of the detector. However we choose to include them below in our discussion of the BDS.

We have not mentioned any involvement in the proposed LC second IP that may serve as a dedicated $\gamma\gamma$ collider. The possibilities have not yet been fully explored by the international workshops, but we note that there is potential here for a major contribution to the design of the IP, especially if the RAL laser division and the VULCAN team play an active role.

Summary

We have identified a range of experimental options for the UK, namely to maintain the success of the LCFI collaboration and to extend UK R&D to the field of novel calorimetry and wider detector issues. This level of activity would ensure that the UK are driving both the tracking and calorimetry at the LC at a total production cost of approximately £35M, which represents about 20% of the total detector cost. We have outlined the case for funding of additional detector R&D at the level of £3.5M over the period 2002-4.

6. THE ACCELERATOR OPPORTUNITY

In the introduction we suggested that our contribution to the LC machine should be on the basis of UK-designed and built accelerator components. This approach is of great intrinsic scientific interest and is also preferable to simply writing a cheque to a common fund to gain entry to the LC physics programme. The aim would be not only to build a substantial and highly visible accelerator system, but also to run and maintain it throughout the life of the LC, possibly using GRID-based technology to run the system remotely from the UK as part of the ICFA Global Accelerator Network. In this way, although the accelerator itself would be based abroad, the UK part of it would be operated and run from a CLRC laboratory and thus would be a visible flagship UK facility. The UK industrial, academic and laboratory based skills and expertise in accelerators and their associated technology would be strengthened and enhanced, increasing the future potential to participate at the highest level in other challenging accelerator based projects both within the UK and abroad.

With this accelerator opportunity in mind, new initiatives have started to re-establish high energy accelerator physics in the UK. In addition to crucial PPARC grants and awards, the CLRC accelerator funding line was vital in setting up this LC accelerator activity, not only by funding staff effort but also by funding LC-related travel, equipment and vital consultancy with the RAL laser division.

We base our case for LC-accelerator activity around two flagship projects: the beam delivery system (BDS) and the damping rings (DRs). Both these projects, described in more detail below, are in line with existing LC-related R&D in the UK and both offer the opportunity for a highly visible and prestigious contribution to the accelerator. The BDS has the added attraction of being close to the experience of the HEP community, being the link between the linac and the detector. The DR has the advantage of being closely related to the design of synchrotron light sources and could utilise the strong existing expertise in this area within CLRC. For instance, there would be a natural synergy with the work on the DIAMOND advanced light source. A balanced strategy would be to adopt a two-prong approach, with the HEP and CLRC accelerator scientists and engineers working together on the LC BDS and the CLRC groups also leading an active collaboration on the DRs. This strategy builds a strong accelerator community across a range of energies from a few GeV to several TeV. Our final commitment to the machine could consist of a major contribution to either or both of these areas, backed up with strong support from UK industry, for example through supplying klystrons for the linac. These possibilities are now discussed in more detail in the following sections.

7. BEAM DELIVERY SYSTEM

The beam delivery system (BDS) of the collider is the region between the ends of the accelerating linacs and the IP. In this section the beams are focussed by quadrupole magnets to the nanometre-scale vertical sizes required to produce high luminosity. The beams are also collimated to remove halo particles and hence minimise the beam-related backgrounds seen by the detector. This part of the machine is thus of great interest to the detector design and the overlap of machine and detector issues is of central importance to the LC physics programme.

Current activity

Both the focussing and collimation functions are vital elements of the design of any future LC, independent of the choice of linac accelerating technology. For this reason the UK has started to develop expertise in beam delivery and is attacking some of the most challenging aspects in a coordinated programme of R&D:

- **Beam Dynamics Simulations.** Detailed simulations are vital to the design of the BDS and a sophisticated code has been developed at DESY, with recent input from Daresbury, Manchester University and RHUL, that tracks the disturbance to the beam in the linac caused by misalignment of the magnets, due to ground or other motions. This allows calculation of the subsequent luminosity degradation due to beam-size blowup, as well as the beam-orbit displacement. In the collider such orbit information needs to be measured and fed forward to the IP feedback system in order to preserve the luminosity on time-scales greater than minutes. Such tracking code methods are also being developed within the UK GEANT4 collaboration.

- **Fast Feedback Systems.** In order to maintain the design luminosity of the collider the beams must be made to collide head-on to within 5 nm. Ground-motion effects near the IP at the relevant bunch-train-repetition frequency (10-100 Hz) are substantial on the nanometre scale, necessitating a fast-feedback system to correct beam misalignments, as well as active stabilisation of the final doublet magnets and the upstream linac components. In order to regain as much luminosity as possible the feedback must respond within 100 ns (TESLA) or within 10 ns (NLC, JLC, and CLIC). Measurement of beam misalignment, calculation of the required correction, and application of the correcting kick within 10ns is exceptionally challenging. Oxford University is collaborating with SLAC, DESY, CERN and KEK on optimisation of the luminosity with an ultra-fast inter-bunch feedback system. The Oxford group has implemented the beam-beam interaction code GUINEA PIG into GEANT models of the NLC and TESLA interaction regions, and simulated the performance of a feedback system. This will also be done for CLIC. The group is now leading an effort to design a prototype system and test it in sector 2 of the SLAC linac: the FONT (Feedback on Nanosecond Timescale) Experiment. Oxford is also investigating application of the Frequency Scanning Interferometry (FSI) technique, being developed for alignment of the ATLAS silicon tracker, to alignment of the magnets at the required μm level in the 20-30 km-long collider linacs.

- **Collimator Wakefield Studies.** Brunel University, via a PPARC Opportunity award, is collaborating with SLAC and DESY on the Collimator Wakefield Experiment, located in sector 2 of the SLAC linac. The design of collimators able to survive the enormous power density (5 MW) in the beams is extremely challenging. The Wakefield Experiment involves testing novel collimator structures and materials in the SLC beam, as well as performing advanced finite-element-analysis simulations in an attempt to understand the data.

- **Photo-injector.** The photo-injector and the thermionic gun are the two options under consideration for the electron sources for the LC. The photo-injector approach offers major advantages and a joint RAL/CERN programme is in place to develop and fully assess this option. The photo-injector uses short laser pulses to illuminate the photo-cathode of an RF gun powered by a klystron in order to generate an electron beam with a momentum of several MeV. In this way the required sequence of bunches can then be directly injected into the drive-beam and low emittances obtained. A paper design study was completed in 2000 showing that a photo-injector laser could meet the required specification cost-effectively. They are now in a two-year R&D programme to resolve the major uncertainties of the design, these being the photo-cathode (CERN already have promising results) and a number of aspects of the laser performance (being tackled jointly by RAL and CERN). Following completion of this R&D project in 2002 they aim to provide a laser and photo-cathode system by 2004 to operate on the next CLIC test machine (CTF3).
- **Laser Based Beam Diagnostics.** This is a new experimental activity, in collaboration with DESY, SLAC, CERN and KEK. Traditionally, solid wire scanners have been used to measure beam-spot sizes of several microns, however they will not withstand the bunch intensities at the LC. A different approach, pioneered several years ago for measuring the micron-size SLC beams at SLAC, employs precision laser optics to scan the electron bunches, the bunch size being determined by counting the resulting Compton-scattered photons. A new optical laboratory is being assembled at RHUL, in collaboration with the RAL laser division, to develop novel laser-wire scanning techniques and to test them at existing machines; PETRA at DESY, CTF at CERN or the ATF at KEK are possible host facilities. Future extensions of this initiative could include the measurement of nanometre-scale beam-spots using interferometric techniques, or a wider class of laser-based beam diagnostics such as the design of a Compton polarimeter.
- **Helical Undulator**. The production of positrons of sufficient quantity and quality for future LCs is currently a hot topic and, as mentioned in the physics section, positron polarisation can increase the effective luminosity of the machine in some channels by significant factors. Various methods are being considered internationally. The TESLA collaboration intend to create the polarised positrons with high energy (gamma ray) synchrotron radiation generated by the electron beam passing though a state of the art helical undulator. Daresbury Laboratory is ideally placed to specify and design the extremely demanding undulator, which will either be made of permanent magnets or be a superconducting electromagnet. This magnet will have a very short period, high magnetic field and will be at least 100 m long. A design could be developed over the next year, with a prototype of 1 m length being built and tested over the following year. The advanced undulator design will be of direct interest to the FEL and light source communities as well as to other LC laboratories.

The current PPARC-funded manpower amounts to a total of 7.5 posts, from a variety of awards and grants, all of which are due to terminate during the period 2002-4. The corresponding average number of already-funded FTEs over this period is 3.3.

R&D Request for 2002-4

The BDS is a £100M project, in which the UK could take a dominant role. It pushes a number of basic technologies to unprecedented limits: alignment of structures to microns over distances of many kilometres, feedback system activation on nanosecond timescales, measurement of beam-spot sizes on nanometre scales.

The current programme of new initiatives and responsive-mode funding has already put the UK in a credible position to propose an expansion of this exciting BDS activity. In order to build on the successes of the last two years, more staff are now needed, both in the universities and in CLRC, to capitalise on this momentum and learn the tools of accelerator physics in advance of the imminent LC construction period. In the following we assume that one FTE costs £45k salary +£5k travel per year (for an adequate presence at the international laboratories). With a modest amount of R&D funding, significantly above the levels currently committed, the UK could develop the expertise to take lead roles in the following areas:

- **Beam dynamics simulations and BDS design:** 3 FTEs to develop beam dynamics code, plan linac stabilisation and feed-forward systems, and global design: £150k *p.a.*
- **Feedback on nanosecond timescales:** Design and fabrication of fast output beam position monitor, kicker magnet, and prototype electronics: £100k, 3 FTEs to develop and test hardware: £150k *p.a.*
- **Accelerator alignment to micron level:** Optics, lasers, amplifier, DAQ £100k, 1 FTE to develop and test hardware £50k *p.a.*
- **Laser-based beam diagnostics:** Optics for Compton polarimeter and nanometre-scale interferometer: £80k, mode-locked laser plus supporting RF electronics £120k, 3 FTEs to develop and operate laserwire, polarimeter and interferometer £150k *p.a.*
- **Laser photoinjector:** 1.5 FTE to build the CTF3 system at CERN £75k *p.a.* and equipment £250k.
- **Collimators to withstand 10^{18} Wm^{-2}:** 2 FTEs to develop novel materials/designs of collimators £100k *p.a.*
- **Helical undulator for polarised positrons**: 2 FTEs to design and build 1m prototype: £100k *p.a.* Prototype costs: £200k.
- **Global BDS management:** During the period 2002-4 and in the light of international decisions, these projects will need to be coordinated into a centrally managed BDS collaboration. A 1 FTE full-time manager will be required for this task, starting in the year 2003: £50k.

The additional funding required for this realistic and balanced programme over the two-year period 2002-4 amounts to £2.1M, after subtraction of the already-funded posts.

At present there is no UK-based facility that could support the testing and development of these frontline projects. While much progress can be made by negotiating time at international facilities, it would be advantageous to our wider BDS ambitions to have an electron test beam designed and run by CLRC, providing electrons with energy of a few GeV. In addition to furthering the accelerator work such a facility would act as a test-bed for industrial prototypes in advance of the LC construction phase and also provide an ideal test beam for detector R&D. This project would require a specific costed proposal and is not addressed further here other than to flag it as a very interesting possibility.

The UK Beam Delivery System

We recommend that the UK position itself to lead the construction of the LC BDS via a partnership between CLRC, the university community and industry. The UK has well-suited industrial expertise in magnets, vacuum engineering, optical technologies, electronics and control systems. CLRC has 30 years of experience in designing electron beam-lines and associated diagnostic systems. The universities are experts in advanced simulations and cutting-edge engineering and hardware construction. The nature of the BDS is very closely linked with the experience of HEP physicists and has a direct bearing on the interaction region, vertex detector and low-angle calorimetry, where the UK already has much interest. The size of the team that we propose building in the previous section is on the right scale to tackle the BDS head-on, with crucial technical and managerial support from CLRC. The project management infrastructure being developed by CLRC for DIAMOND, a project of comparable scope, could be extended to the BDS.

8. DAMPING RINGS

All the proposed LC designs need two damping rings (DRs), one for the electrons and one for the positrons. Establishing leadership in the detailed design of the DRs will place the UK in a strong position to take on the responsibility for the technical build and installation of any such complex.

The DRs are placed between the particle sources and the start of the main linac. High luminosities at the IP depend on very small beam sizes. Since the beam size is a function of the emittance of the beam, it is necessary to make this as small as possible to reach the required luminosity. The equilibrium emittance is a balance between quantum excitation and radiation damping, processes that take place at a relatively low level in the main linac and BDS. A DR is therefore used before the main linac to reduce the emittance by many orders of magnitude, by radiation damping. In order to minimise the delay between bunch trains, the damping time must be short. This is normally achieved by long insertion devices producing powerful beams of synchrotron radiation. One design of a DR for CLIC, for example, uses 10 wiggler magnets for producing radiation and specifies a damping time of 37 μs. A large circumference allows several bunch trains to circulate simultaneously, but adds considerably to the cost of the ring.

A good design for a DR would include very low emittance, short damping time, and minimum circumference. Therefore, there are many features common between DRs and synchrotron light sources, on which there is considerable expertise at Daresbury Laboratory. The DR could be one part of the machine for which the UK could take primary technical responsibility. The design and construction of DRs for a 1-3 TeV collider, such as CLIC, is a challenging project, and there will be considerable spin-offs in areas such as RF and control system technology. Although the DR study is initially motivated by the need for a design for a particular collider, much of the technological development would be generically applicable to any of the LC projects proposed.

Bunch trains are carried to and from the DRs along transfer lines that must preserve beam quality. The particular challenges here are that some of the transfer lines are of considerable length. In TESLA, for example, positrons would be produced in pair creation from photons generated by a wiggler magnet at the end of the main electron linac. Carrying the positrons to the DR requires a transfer line of several kilometres. The transfer lines are not always straightforward lattices of bending and focusing magnets, but usually include other systems, such as bunch compressors and spin rotators, and will be important locations for a wide range of diagnostic instrumentation.

A significant benefit of DR research will be an improvement in the understanding of, and design techniques for, accelerator storage rings and insertion devices in general. Applying the new skills and knowledge to synchrotron light sources, for example, would enable these machines to achieve still higher performance than is currently possible, and will benefit a wide range of subjects from structural biology to surface science.

Strategy

The experience within CLRC of electron storage rings, in particular the current design work on the advanced light source DIAMOND, means that DR design is a compelling area for UK involvement. The DR and light source designs have a very large overlap in both engineering and physics and, with the funding of the DIAMOND project, the UK will build one of the most advanced machines in this class. Given the size and expertise of the group necessary for this activity, it is natural that this team should take a leadership role in DR design for the LC. Both NLC/JLC and TESLA have developed conceptual designs for the DRs before the UK initiated involvement in LC design work. However, a technical solution for 3 TeV CLIC requirements has yet to be demonstrated in detail and, using very limited resources, Daresbury physicists are proving that they can contribute to developing a solution. Furthering this effort is part of a three-step strategy for UK involvement:

1. Occupy *the* prime position to produce a fully costed design of the CLIC DR complex.
2. Make a significant contribution to the build, operation and development of the LC DRs including major component parts of these rings, to include injection/extraction systems, damping wigglers, magnet system, RF, vacuum and diagnostics.
3. Bid later to take sole responsibility for the technical build, operation and development of the whole CLIC DR complex, the most technically challenging DR project.

Current Activities

CLRC has a number of accelerator physicists and accelerator engineers whose main activities are the support and design of synchrotron radiation sources but who take an active interest in DR design issues. Although technically feasible designs have been produced for some of the options for NLC/JLC, TESLA and CLIC (1 TeV), a good understanding of how to optimise these designs is lacking as yet and a technical solution for 3 TeV CLIC requirements has yet to be demonstrated in detail. Some work at CERN has been carried out to study analytically the optimisation of such rings using computer algebra codes, but further work is required to generalise this and to examine higher-order effects on the optimisation, such as the effects of multipole wigglers, intra-beam scattering and lifetime. Present simulation tools (such as MAD) allow local optimisation from a given starting point, but do not give a global optimum. In addition, they do not include all of the effects, which are relevant to a DR design. Circular accelerator design is currently being optimised using computer algebra and the relevant new software is being produced.

R&D Request for 2002-2004

For the DRs, the most fruitful direction to pursue at present is to continue the collaboration between Daresbury Laboratory and the CERN CLIC project, while building wider collaboration with the LC groups. The development of the base design into a UK project to construct the LC DRs will involve designers and engineers from many laboratories. It is essential fully to involve universities and industry in this R&D to ensure that the UK accelerator base, both academic and industrial, can exploit the opportunities available from participation in this LC project. This programme will produce a core group of 20-25 accelerator experts, a significant UK resource.

Funding for a major DR activity is requested, translating physics studies into a comprehensive Technical Design Report, complete with cost. Based on similar light source study experience, a detailed estimate of associated resource needs has been made. In practice, most of the staff will need to be drawn from the CLRC skill base that is uniquely qualified (in the UK) to perform these functions.

- 20 FTEs at standard staff rates, amounting to a total of £2.1M over this period. Most of this will be engineering/technical effort involved in the design of the many specialist systems.
- During the design phase, prototype systems for the DR and DR transfer lines must be developed to test the challenging engineering and physics issues. Cost of prototypes: £200k.
- Travel costs, at a level of £50k annually for this team.

The total funds required for this programme in the period 2002-4 amount to £2.4M.

Projected UK Role (2004-2007)

A DR complex forms a significant part of the accelerator with an estimated cost in the region of £200M. As with all large accelerators, the component systems would have to be built in partnership with industry, either through collaborative R&D projects or by direct contracts for specified system or components.

The aim is to achieve control and leadership of a significant fraction of the LC DR complex with UK groups running major component parts. The involvement would continue throughout the lifetime of the collider with UK teams running the facility from a home-based control room facility (as for the BDS proposal) and by providing the support for development, upgrades and improvements in the defined areas. As for the BDS, the UK DR would be a visible flagship UK facility.

9. GENERIC TECHNOLOGIES AND INTERACTION WITH INDUSTRY

Introduction

Specific areas in which the UK can make a large contribution to the LC have been presented in earlier sections of this document. However, the UK also has significant industrial expertise in several technologies of importance to accelerators in general and the LC in particular. These are discussed in this section and mention is made of some of the companies involved together with the possible wider impact of developments made for the LC. It is worthy of note that many of these technologies have benefited strongly from developments made for particle physics, and are now used in a broad range of medical and industrial applications. Improvements in RF power generation could benefit, for example, radio and television broadcasting, radar and telecommunications as well as improving particle accelerators for scientific, industrial and medical purposes. Superconducting magnets are used in magnetic resonance imaging devices in hospitals throughout the world and find application in the mineral extraction industry, where they make possible highly efficient separation on the basis of magnetic properties. They are also used to control convection currents in the growth of the large diameter silicon crystals crucial to the electronics industry.

High Power Radio-Frequency Engineering

The LC requires a large amount of RF power in order to accelerate the electron and positron beams: at 500 GeV centre-of-mass energy, the superconducting TESLA design requires about 600 klystrons, each capable of delivering a peak power of about 10 MW, with the attendant high voltage power supplies and modulators. This requirement approximately doubles at an energy of 800 GeV, but even this number is dwarfed by the 7 000 high-power klystrons necessary to operate the normal conducting NLC. The development of these devices presents considerable scientific and technical challenges, as improvements in the efficiency, reliability, spectral output and power of RF systems are required, in conjunction with cost reductions. These goals can only be achieved through advances in science and engineering in areas such as:

- Surface physics, particularly primary and secondary emission, DC and RF breakdown mechanisms.
- Materials science, study of ceramics and permanent magnets.
- Computer simulation, “right-first-time” design through advanced electromagnetic modeling.
- High frequency and high voltage power conversion.
- Control and monitoring systems.
- Vacuum and superconductor technology and manufacturing techniques.

Above and beyond the immediate benefits for the LC, advances in RF power engineering will have impact in the areas mentioned in the introduction to this section. Many other fields will also benefit, however. Considering only the accelerator developments facilitated by improved RF systems, some of these are:

Engineering, physical and biological sciences. Free electron laser based fourth generation light sources will allow investigations of surfaces, of novel materials, time resolved studies of protein folding mechanisms and a wealth of other topics as documented in the CASIM proposal [7]

Medicine. Compact sources of synchrotron radiation will make possible new and powerful imaging techniques, proton and heavy ion accelerators will improve the efficacy of radiotherapy.

Nuclear waste management. Accelerator driven transmutation of nuclear waste allows conversion of extremely long-lived radioactive isotopes to those with manageable lifetimes.

Power generation. The possibility of generating electricity using sub-critical fission maintained by accelerators is being actively investigated in Europe. In addition to the inherent safety offered by sub-critical operation, this technique produces waste with half-lives orders of magnitude smaller than conventional fission power plants

The UK is fortunate in having significant expertise in the field of RF power engineering. Marconi Applied Technologies is one of only three companies worldwide awarded a contract to work on RF power issues for the NLC project. A second UK company, TMD technologies, is recognised as a European centre of excellence for cathode and electron gun technology and designs and produces high power klystrons, as do Marconi. However, uncertainties in the scheduling and funding of the LC make it difficult for these companies to justify the development of klystrons *etc*. for the LC on a purely commercial basis, so funding at the £1M level is needed in the next two years to perform the necessary R&D. (Note that Marconi and TMD's competitors in the USA are known to receive DoD and DoE funding to support such basic R&D. Similarly, their French rivals are supported through DRET.) These companies have therefore formed a Faraday partnership with the Universities of Lancaster, Strathclyde and Oxford and with the CCLRC Daresbury and Rutherford Laboratories and are seeking funding through that route. This endeavour should be supported and alternatives sought if the Faraday initiative is not successful.

Superconducting and Magnet Technology

The LC will require a large number of magnets, some superconducting, for the steering and focussing of the beams. In addition, if the LC is of the TESLA type, a large amount of superconducting infrastructure will be necessary to keep the superconducting cavities at their operating temperature of about 2 K; the installation will be of a similar size to that needed for the LHC. Again, this presents challenges and opportunities for some of the UK's most technologically advanced companies, including Oxford Instruments and Tesla Engineering.

Oxford Instruments is an internationally renowned company with acknowledged expertise in many aspects of superconductor technology, from the production of superconducting wire and cable to the design and construction of the complete cryogenic systems and superconducting magnets used in MRI systems. They also have experience of working for high-energy physics experiments and accelerators, for example they produced the Cleo II magnet used on the Cornell storage ring and have designed and tested the large aperture low-β insertions for the LHC. The Rutherford wire used in the latter, originally developed at RAL for high energy physics, has found widespread industrial application. Oxford Instruments have invested considerable effort in increasing the efficiency of the cryogenic systems for their magnets, which means they are both ideally placed to provide systems for TESLA, where the large scale will make efficient operation mandatory, and able to exploit developments made for the LC in a broader context.

Normal and superconducting magnets are also the area in which Tesla Engineering specialises. This UK company has designed and supplied magnets for accelerators. Again, the uncertainties with respect to the timing of the LC make it difficult for these companies to undertake the design work necessary to compete on the world stage for LC contracts, unless support is provided. Discussions as to how this may be achieved have been initiated.

Vacuum and Beam-line Technology

A further area in which UK is able to make a contribution to the LC is in the field of vacuum and beam-line technology. The company Oxford-Danfysik, formerly the accelerator division of Oxford Instruments which constructed the Daresbury designed Helios synchrotron for IBM, now provides complete beam-lines for synchrotron radiation users. Oxford-Danfysik work with Thermo Vacuum Generators and together would be capable of contributing to the design and construction of beamline elements for the LC.

Summary

The construction of the LC presents significant opportunities for UK industry. These require some early funding in order to allow UK companies to do the R&D necessary to profit from the LC. The spin-offs from this investment are considerable. While the payoffs to industry will be enormous, in the current absence of a specific decision on the international LC the risks are substantial. We recommend that a £1M contribution to the startup risks of klystron design be made available, ideally within the context of the proposed Faraday Partnership.

10. SUMMARY OF ACCELERATOR FUNDING REQUESTS

The LC will be a major international project costing several billion pounds. The UK should position itself now to take a credible role in the construction of a significant component of the machine, if it is to play a role in the LC that is commensurate with its current first-rank standing in particle physics. The UK contribution to the LC machine should preferably be channeled through UK industry, which would thereby also benefit by collaborative access to technology and expertise in CLRC and the universities.

We have proposed a balanced programme of accelerator R&D involving CLRC, UK universities and UK industry. The programme has already been initiated with PPARC funds from a variety of schemes and forms a sound basis for UK leadership in the LC, CLIC and beyond. The requested R&D funds for the period 2002-4 sum to £5.5M and are summarised here:

- Beam Delivery System: £2.1M.
- Damping Rings: £2.4M.
- Klystron R&D, possibly via an already proposed Faraday Partnership: £1.0M.

11. SUMMARY

Through the foresight and efforts of many UK particle physicists and of PPARC itself, the UK is now well placed to take advantage of the excellent opportunities in LC physics. A programme encompassing physics studies, detector R&D and accelerator R&D is now establishing itself and the way ahead is becoming clear. We have outlined a strategy and budget whereby, over the period 2002-4 the UK can

- extend its expertise in detector design involving both tracking and calorimetry: £3.5M
- build on the growing accelerator R&D activity: £5.5 M

The LC will be the next major particle physics facility. Decisions on its realisation could be made as soon as in 2002. If the UK is to maintain its top ranking, a programme of detector R&D is now urgent. The financing of the machine will require international agreements, however UK participation in the design, construction and running of a significant accelerator sub-system provides an excellent way forward towards a contribution in kind. The accelerator R&D proposed here is the first step to achieving this.

Acknowledgements

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