Linear Collider Flavour ID (LCFI) Collaboration

P306 - Progress Report
22 Sept 2001

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1 Introduction

The LCFI Collaboration is working on the development of a vertex detector for the future TeV-scale e^+e^- linear collider, and associated physics studies to steer the detector design and explore the potential for physics. This project was approved by the PPESP for an initial R&D programme in October 1998. We submitted a status report and proposal for an expanded programme, matched to the current linear collider requirements, in March 2001. Startup funding for this programme was awarded by the PPESP in May 2001. The international situation has advanced significantly since March; these developments are discussed in Section 2. Progress in our R&D work is described in Sections 3-5, and in Section 6 we discuss the status of our physics studies. In Section 7 we summarise the current funding situation and our proposal for continuation, and in Section 8 we list the manpower position for our project. As an appendix, we include the proposal we have submitted to the Basic Technology Research Programme.

2 International perspective

On the international scene, the period since March has seen three major developments relevant to the future linear collider. The launch of the TESLA project in DESY alerted the scientific community to the fact that construction of such a facility is now feasible, and to the great potential for a broad range of science. Secondly, the Snowmass Workshop resulted in an unprecedented consensus within the US HEP community. The unanimous statement at the end of the workshop from all the physics working groups contains the sentence "We therefore strongly recommend the expeditious construction of a Linear Collider as the next major international High Energy Physics project". Thirdly, the ECFA Panel set up to recommend the next major steps for particle physics, under the chairmanship of Lorenzo Foa, came to the same conclusion.

The LCFI proposal was presented to the DESY Programme Review Committee on 17 May. The conclusions of the referee Karl-Tasso Knöpfle contain the sentence "Compared to alternative vertex detector technologies, the proposed approach exhibits the highest potential for reaching ultimate performance". The report from the committee states "Based on the recommendation of the referee, the DESY directorate in its session on 23 May 2001 has approved the proposal under the number PRC R&D 01/01. We have been impressed by the high quality of the proposal and are looking forward to its successful completion".

It was decided at Snowmass to form a small international group (3 physicists per region) to develop various ideas for enhancing R&D on detectors for the future LC, a sort of 'global detector network' which mirrors the embryonic global accelerator network. Damerell is one of the Europeans appointed to this group, which has as one of its major goals the international sharing of ideas and resources so that, when the site for the new machine is selected, every physicist doing R&D will find a comfortable home within which to move on to the stage of forming collaborations and building real detectors. The LCFI collaboration has close links with the CCD development groups in the USA and Japan, and expects to exchange test devices with our international colleagues, as the programmes advance.

M Breidenbach gave a talk at Snowmass (repeated 3 times at request of various working groups) entitled 'Why the desired LC detector can't be built (without a major R&D programme)'. The rapid advances by the accelerator community on TESLA and NLC have triggered a major worldwide initiative on detector R&D. The LCFI collaboration played a pioneering role, but has now been joined by many others. Overall, there is a good chance that vertex and other detectors satisfying the challenging performance requirements will emerge in time, from the many R&D programmes under way. For example, there are now four technical options being developed for the vertex detector (CCDs, hybrid pixels, monolithic pixels and DEPFET pixels). Note that these are all some form of silicon pixel detector, and hence stand on the shoulders of the 307 Mpixel detector which proved so valuable for physics at SLD. The increased number of pixel detector architectures to have emerged since then gives grounds for confidence that the much more challenging requirements at the future LC can be met, provided adequate R&D programmes are maintained.

3 Detector test systems

We continue to develop CCD test systems at RAL and in Liverpool. A number of problems emerged in the original plans, most seriously a long delay in the production of 'generic VME modules' from the ESD group at RAL. This triggered an intense re-evaluation period last April, which was led by Konstantin Stefanov, the recently arrived RA at RAL. As a result of a massive effort by Konstantin and Bob English, a new DAQ system was conceived and implemented, consisting partly of commercial VME modules and partly of in-house designs, controlled from a PC running LabView.

As a result of their efforts, the complete RAL-based detector test system has been commissioned. Using a fast CCD from Marconi Applied Technologies (MTech), it has been possible to obtain beautiful signals from an Fe^{55} X-ray source (approximately equivalent to min-I particles) with extremely low noise (68 e^- rms) clocking the system at 10 MHz, as shown in Figure 1. This noise/speed combination is a world record, and is already close to the Phase 3 goals for our R&D programme, albeit with a linear CCD register for the time being. Even higher speed clocking will become possible once the final module in the system (the drive control module from the ECD group) is delivered next month.

We are rapidly converging on a DAQ system which will be well matched to the requirements for the test devices to be produced by MTech in the first phase of the column parallel development programme.

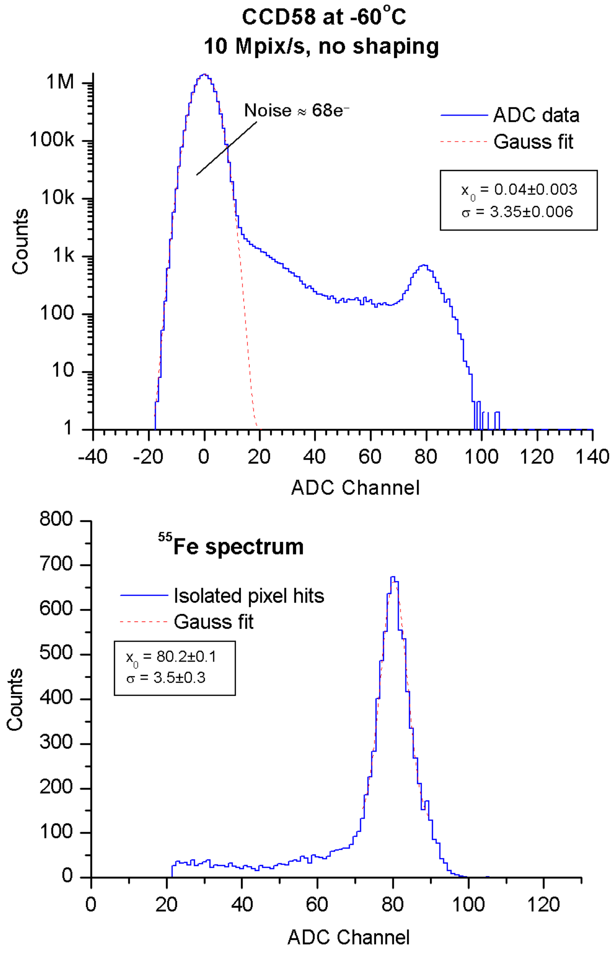

Figure 1 Fe^{55} spectra (5.9 keV X-rays) from CCD58 with serial register operating at 10 MHz. Top plot: raw data. Bottom plot: isolated pixels hits.

The corresponding test system at Liverpool University will be used primarily to study radiation effects. We now have a leak-tight test enclosure and are commissioning the optical system, and the temperature control system which will permit operation at or below liquid nitrogen temperature. This will be of great importance in studying fundamental aspects of radiation effects in silicon.

4 Column parallel CCD development

Since May, when the PPESP gave approval for work to begin, we have entered into an extremely promising collaboration with MTech. People putting a large part of their time into this are Konstantin Stefanov, Steve Thomas (from the RAL Instrumentation Department) and staff at MTech. We have held a number of decisive meetings, including other physicists from PPD and Liverpool University. The new people have produced new ideas such as direct connection from CCD without source follower, a scheme for noiseless clock feedthrough cancellation, and very low power ADCs. It is extremely satisfying to see

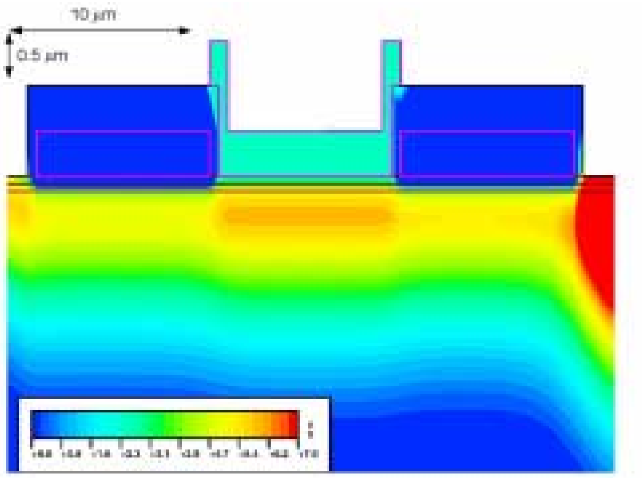

Figure 2 Potential distribution in cross section of buried channel CCD structure. Storage region for signal electrons is below the central (positive) gate. Voltage range is 0 to 7 V.

the interaction between electronics experts with a particle physics background, and others with a CCD background. This has resulted in a fast two-way flow of information, augmented by the interest (but not yet direct participation) of the groups drawn in by the Technology Fund bid.

The original proposal called for just 3 production runs of test devices, each preceded by a lengthy design stage. It has recently emerged that MTech can make available to us a much more dynamic, responsive and cost-effective option. For their own R&D, they use part of the test field reserved on the wafer mostly for a large number of devices used for QA of the production process. They have agreed to use this area (which can be as much as 15×4 mm^2) for our project. This has the enormous benefit of providing a 'free ride' on new products moving through design, mask making and wafer fab. This approach will permit a wide range of architectures to be tested, and revisions to be made relatively quickly and cheaply. The selection of precisely what to include in the first test devices will be taken at a meeting with MTech in mid-October, hopefully including the CCD experts on our Technology Fund bid. Assuming that either this fund or the PPRP will be able to support the project next year, we can expect the first column parallel CCDs to become available in the latter half of 2002.

Some ideas are extremely speculative. To test all of them would be prohibitively expensive and time consuming. Since 1998, when the PPESP generously allocated funds for the ISE TCAD software, we have been hoping to supplement our back-of-envelope calculations with full simulations. The problem was to find someone with a deep understanding of CCDs to drive these studies. Fortunately, Konstantin Stefanov joined us with a very strong CCD background. He is currently making extremely fast progress in modelling the full complexity of the CCD structure, plus output stage, with the ISE software. An example of the modeling of a buried channel CCD structure with realistic metal buttressed polysilicon gates is shown in Figure 2. Konstantin’s work is being used to narrow down the options for the first round of test devices.

Our CCD test facilities at RAL are nearing completion; the upgrade from 10 MHz to 50 MHz capability will take place next month. However, to test the column parallel devices, we require additional electronics. First and foremost, we need a readout chip from the RAL microelectronics group. Secondly we need a test card matched to the layout of the new

CCD, replacing that currently used for the CCD58 devices. Thirdly, we need some novel electronics in order to operate with high speed 2-phase sinusoidal drive pulses. The Oxford University electronics group in the Physics Department has considerable experience with high power RF, and Johan Fopma has joined our collaboration to work in this area.

The final requirement for the new system is a means to make the connections between the CCD and readout chip. Here we will start by mounting this chip face up and wire bonding 1 in N channels (N ~ 10). However, the mechanical design will permit an assembly with the readout chip inverted, and all channels connected by bump bonding. Initial discussions with one bump bonding company were rather negative, but we have since learned of two more which are much more promising. What was really lacking was adequate expertise and time within our small group to deal adequately with this complex part of the project. We have recently been extremely happy to see this problem solved (potentially) by the participation at a low level of Jeff Bizzell in our project. Jeff is required nearly full-time for ATLAS, but has kindly agreed to work with us in his spare time. His expertise in this area is precisely what was needed to get this part of the project moving.

In summary, the team is in place and is extremely keen to deliver the world's first column parallel CCD during 2002. As can be seen from our Technology Fund bid (Appendix A) this development will be of importance to scientists involved in imaging applications across a wide range of research.

5 Mechanical R&D programme

We retain the two main options of supported and unsupported silicon. The former is based on 20 μm thick silicon bonded to a beryllium substrate in the form of a V-frame (leading to 0.12% X_0 total ladder thickness) and the latter is based on 60 μm thick silicon stretched between a pair of blocks (0.06% X_0). As reported last March, we were able to demonstrate excellent mechanical stability for an unsupported silicon assembly operated at room temperature. Since that time, a number of further issues have been addressed, including effects of cooling to the operating temperature of ~ 200 K, possible need to use adhesives compatible with solder bump bonds (as opposed to indium), and requirement of metal buttressing in CCDs matched to TESLA (differential contraction issues).

Our manpower for this work consists primarily of Wing Lau, head of the Mechanical Engineering group in the Physics Department at Oxford University, Erik Johnson, a support physicist at RAL, and Glenn Christian, a CASE student at Oxford University. They have been making excellent progress, but the assembly of each engineering model ladder is a major task, and there are more ideas than one could realistically study experimentally. Since Wing Lau joined the team, his use of some very powerful FEA thermo-mechanical simulation software is rapidly narrowing down the phase space for possible solutions.

6 Physics studies

The report published in association with the TESLA TDR [1] provided an important new insight into the performance achievable with flavour ID in TeV-scale e^+e^- collisions. The basis of all flavour ID studies for the future linear collider is David Jackson's program ZVTOP, developed originally for SLD. This program is structured to make optimal use of a high precision pixel-based detector. In the European studies initiated by Richard Hawkings and taken over by Stefania Xella Hansen when Richard moved to ATLAS, ZVTOP is the

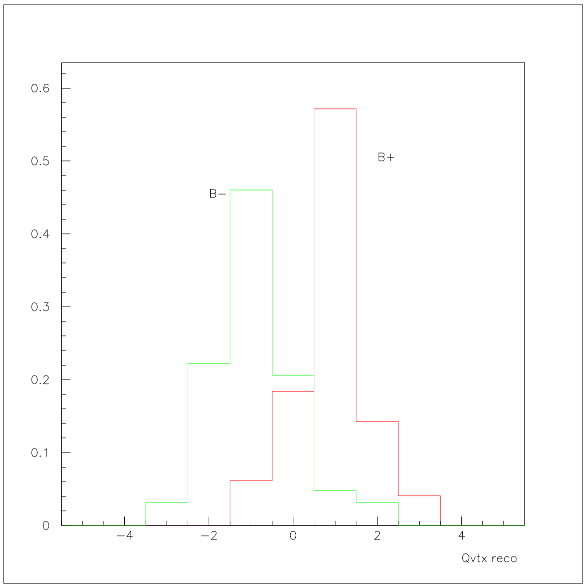

Figure 3 Measured vertex charge distribution for hadronically decaying B^+ and B^- mesons (very preliminary).

core of a neural net analysis which also uses information from various other event characteristics.

By the time of the TESLA TDR, Stefania had the program fully tuned at $\sqrt{s}$ = 92 GeV, and was able to extend to 500 GeV with monojets. This provided the first insight into the factors affecting the high energy performance. For Snowmass, she greatly extended the studies with completely physical $e^+e^- \to q\overline{q}$ events.

Stefania is currently on maternity leave, but she will take up these studies again in the near future; in fact she is already working from home and contributing valuable ideas. Meanwhile, Matthew Wing of Bristol University has joined the project, and is making excellent progress. Being based in DESY, he is well able to interact with the centre of gravity for the European software. He presented the current state of the simulations at the most recent ECFA / DESY workshop, held last week in Krakow. He was able for the first time to show the preliminary performance for the determination of the vertex charge, seen in Figure 3. This subtle measurement, pioneered in SLD, will be of paramount importance at the future LC, due to its capacity for suppressing the combinatorial background in multi-jet events, as well as for unambiguously defining the final state in many important physics channels. Once this simulation is tuned, it will be valuable in feeding back physics-based performance goals for the detector system. This will be particularly important in order to determine the detector thickness really needed for the physics.

7 Funding situation

At its meeting on 14 May, the PPESP awarded a budget of £100K to the project, which included £75K for the first 3 months work with MTech. In line with this, we have placed a contract which will lead to a preliminary design report. We now request the allocation of a further £75K (conditionally agreed in the May PPESP meeting) for which the deliverable will be the final Phase 1 design report and the detailed design of the test devices referred to in Section 4. This support will enable us to keep the project afloat till the end of this financial year.

As suggested to us by the PPESP, a major part of our efforts since March have been devoted to building up a powerful consortium across many areas of science, culminating in a proposal to the Basic Technology Research Programme, which is included as Appendix A to this document. It should be explained that this bid exceeds that made to the PPESP, due to the much broader scope of the proposal. With eight participating groups from areas of science other than particle physics, their requirements for different readout chips, test facilities and four PDRAs inevitably increased the budget request. However, their enthusiastic participation in the proposal reflects the potential importance of the column parallel CCD for science. Not only potential end users but also world-leading CCD experts such as Andrew Holland and Nick Waltham have joined the proposal. Their ideas have already enhanced the design concept. If supported by the Technology Fund, our project will undoubtedly be strengthened by this broader collaboration. We have worked hard and prepared a proposal which offers the prospects of a major breakthrough in scientific imaging. However, this fund has been so over-subscribed that many excellent proposals will inevitably be rejected. We would therefore like to ask the PPRP to consider not only the issue of funding for the next three months, but also how to ensure the longer term survival of the project if not supported by the Technology Fund. In this case, the LCFI Collaboration will need a period of stable funding in line with the request in our proposal of March 2001, allowing us to focus on the technical challenges which we have only begun to address.

8 Manpower

These comments relate to changes with respect to the situation summarised in Appendix C of the proposal of 19 March 2001.

Bristol University

Matthew Wing is the RA who was anonymous in the table. His work leading up to his presentation at last week's ECFA/DESY workshop was extremely important, and the extension to broad physics studies by the time of the next workshop will be crucial.

Bristol is in the process of recruiting a second RA, who will be 50% on the LC work. This welcome increase goes beyond the table of last March.

Liverpool University

So far, the work has been restricted by the lack of students or RAs, and this situation continues for the present. However, Leo Carroll is finding much more time for LCFI than in the table (more like 60%) and this is extremely valuable.

Oxford University

Here we have benefited greatly from a number of new participants. Susan Cooper, Wing Lau and Johan Fopma have considerable relevant experience, and are making major contributions to the project.

RAL

The team of Marcus French and Steve Thomas is driving the readout chip design, and injecting important new ideas into MTech, as previously noted.

Konstantin Stefanov had not yet joined the group at the time of our proposal. His enormous experience, enthusiasm and energy has transformed the situation at RAL, both in the lab and in the device simulations.

Having Jeff Bizzell join in to spearhead the bump bonding (albeit at a small percentage of his time) promises to fill a serious gap with someone having precisely the required knowledge and experience.

The only serious problem with the RAL group is our ongoing inability to fill the position of deputy group leader. This problem has persisted for two years and implementing a solution is now urgent.

References

[1] S Xella Hansen et al LC-PHSM-2001-024 (DESY LC Note)

Appendix A

Outline Proposal to Basic Technology Research Programme

The Column Parallel CCD: A Breakthrough in Scientific Imaging

Introduction

Since the invention of charge coupled devices (CCDs) 30 years ago, sustained developments by hundreds of scientists and engineers have led to their evolution into a rich family of detectors of photons and other types of radiation. As recently as 1999, they overtook image plates as the most widely used technology for X-ray diffraction systems. However, their use in science and technology is often restricted by one or more of three limitations: readout speed, power dissipation and radiation resistance. This project will marry CCD technology with the rapidly evolving CMOS technology for readout, thereby dramatically strengthening CCD imaging systems in each of their weak areas, while preserving all their precious attributes. New windows will be opened in optical and X-ray astronomy, earth observation, particle detection, synchrotron radiation (SR) applications including protein crystallography (PX), and biomedical imaging systems. There will also be spinoff into industrial areas such as on-line inspection and particle imaging velocimetry.

While this proposal is driven by a number of scientific goals, we expect that imaginative scientists will use these high performance imaging systems, once they become available, to reap rich rewards in areas well beyond the present horizons. A very recent possibility is the combination of this approach with Marconi's newly developed low light-level CCD (LLLCCD), with sub single electron noise performance.

Aims and objectives

a) Readout speed

In any imaging system, the readout speed is related to the required noise performance, which varies widely for different scientific applications. In general, the limitation in readout time of CCDs arises from the bottleneck produced by reading all the pixel signals through a few circuits at the edge of the imaging area. In the present proposal, it is suggested to equip each column of the imaging area with an independent output circuit. It will be possible to make very low capacitance bump-bonded connections from these outputs to amplifiers and signal processing electronics in a single readout chip, with circuits spaced at the column pitch of typically 20 μm, made with a modern deep submicron CMOS process. For a 2 cm wide CCD, this alone will result in a factor ~1000 reduction in readout time, with no sacrifice in optical quality or noise performance. For some scientific detector systems this will suffice, while for others a further speed enhancement by a factor 10 or more is important. The goals of faster parallel register clocking will be addressed in the latter part of the R&D programme.

This 'separated function' approach (fully optimised imaging sensors linked to fully optimised readout chips) will permit extraordinary flexibility. Once specific scientific detectors begin to branch off from the generic programme, each will benefit from a customised readout chip. Within the generic programme, it is proposed to develop two examples. One type will have the ultimate speed capability (tens of MHz clock rate) with modest resolution in signal amplitude (~8 bits) and real-time data sparsification. The other will have more modest speed capability but 16 bit resolution and full frame readout. These extremes would be of interest respectively for particle physics vertex detectors and for X-ray protein crystallography.

b) Power dissipation

For some imaging systems (e.g. in satellites), voltage and power requirements are always important, but this becomes a major concern in *all* systems requiring the highest readout speeds. This programme will therefore explore several ideas for reducing the parallel register clock voltages from ~10 V to 1-3 V.

c) Radiation resistance

CCDs with thin dielectric are relatively robust with respect to radiation-induced charge buildup at surface interface states. They can tolerate ~1 Mrad doses of ionising radiation, which is sufficient for most applications. However, bulk damage effects are more serious, leading to loss of charge transfer efficiency, particularly when irradiated with protons or neutrons. This is of particular concern in space-based and particle physics applications.

Fast clocking in the new architecture will of itself considerably enhance radiation tolerance. Combining this with other ideas (inter-frame charge injection, temperature optimisation, novel supplementary channels) will lead to further enhancements. The world of column parallel CCDs has so far been explored only in conceptual designs. Manufacturing some test devices and studying their radiation damage properties promises to open some very interesting new options.

d) Reduced thickness detectors

New assembly procedures will be developed for devices of overall thickness $\sim 50\ \mu\text{m}$ compared to the typical $300\ \mu\text{m}$, considerably reducing the disturbance caused by the CCD to a particle passing through it. This is of interest for particle tracking and for X-ray systems combining two instruments in succession to achieve wide energy response. The mechanical flexibility of the thin silicon also allows curved focal plane arrays in optical telescope systems and large area mosaics for real-time digital holography.

Significance of the programme

Concrete examples of science which will benefit significantly from this programme are as follows:

- X-ray scattering, particularly
  - high throughput PX (multiple images and multiple samples)
  - time resolved PX for irreversible processes (multiple images)
  - structural genomics (multiple images)
  - XFEL for single-molecule structural analysis (in longer term, still highly speculative)
- dynamic processing of soft condensed matter, particularly polymer quenching
- direct electron detection in electron microscopy (electron diffraction and possibly imaging)
- time resolved spectroscopy (optical and UV)
- earth observation satellites
- curved focal plane arrays
- control of telescopes with adaptive optics
- high throughput X-ray astronomy (e.g. XEUS)
- particle tracking detectors
- 3-D holographic video imaging of biological systems

The breadth of the scientific importance is reflected in the composition and manpower offered to this project by the groups listed in the application form. Specific examples of science now beyond our reach, but which will be enabled by this programme, include high throughput PX at future bright sources such as DIAMOND, velocity measurement of plankton (of major ecological importance), high throughput astronomy, high resolution earth observation systems, and vertex detection at the future linear collider (LC). The LC is the top priority international particle physics project after the LHC, and DIAMOND is the major UK science infrastructure project for the next decade.

Despite the enormous potential of many of these applications, this expensive R&D programme would be beyond the means of any of the relevant research councils individually. However, we believe the proposal to be entirely realistic in the enlightened scenario of inter-disciplinary funding, particularly in view of the commitment of a strong collaboration of world-leading groups covering this wide range of scientific interests.

Nature of the research team and ability to deliver

This new imaging concept has stimulated unprecedented and lively discussions among many of the UK experts in scientific imaging systems; the shared sense of excitement bodes well for the future. This proposal is submitted by a new consortium which brings together:

- leading UK groups which have worked for years on the development of CCDs for various scientific instruments funded by PPARC, EPSRC, NERC, ESA, NASA, and the US DoE
- one of the leading microelectronics design groups within the UK academic community
- leading CCD users who operate at the 'sharp end' of their detector systems

The CCD development will involve a contract with Marconi Applied Technologies (formerly EEV), who will participate in the design, and supply test structures and CCDs for each phase of the project. The participating academic groups have had a long and productive working relationship with this excellent UK company, which is the world's leading manufacturer of science-grade CCDs. Their current financial position is strong, in contrast to that of their parent company.

The proposed manpower for the project (21 sy/yr: see Application Form) requires a modest increment of 4 PDRAs on existing staff levels. These new PDRAs can realistically be recruited next year from excellent graduate students now in post. The participating groups and EEV have a long track record for high level training, as can be seen in the background of numerous world leaders in the field of scientific imaging. The training aspects of this project, which includes two new CASE students, will help alleviate the ongoing shortage of scientists and engineers in this field.

It would be reckless to enter into such a complex R&D programme without a preliminary feasibility study. Fortunately, some of the goals are of particular interest to the particle physics community, and PPARC (through the PPESP) has supported these since October 1998. This R&D programme has made excellent progress, reported in numerous published papers, and the design study for the column parallel concept will be the subject of a formal report at the end of this year. This study has already turned up a number of exciting new ideas, and it could be that in some directions the stated goals will be surpassed.

Proposal methodology and management structure

The generic R&D programme will build on the design study. It will be divided into three stages with progressively enhanced performance goals. Each stage will comprise the following R&D cycle:

- advanced design work using the sophisticated ISE-TCAD tools (already in use for the design study)
- manufacture of test structures at Marconi, their evaluation, and feedback to tune the designs
- manufacture of CCDs, of readout chips, and of assemblies (wire bonded initially, then bump bonded)
- evaluation of these assemblies in lab test systems and in an X-ray beamline at the SRS, Daresbury.

The project will be managed along the lines of successful CCD R&D projects over the past decade, for example the development by an international collaboration of a 300 Mpixel particle detector for the SLD experiment at SLAC in California, with a similar budget to the present proposal. The Management Board (Manager and Co-investigators) will appoint Principal Investigators (PIs) for each technical area from among the participating institutions. The main communication channel will be monthly video conferences, with document sharing on the Web, and 6-monthly full collaboration meetings. The budget will be distributed among the co-investigators and the spend controlled by delegated signing powers to the PIs. This structure is already in place and working well for those institutions participating in the PPARC-supported R&D programme.

Take-up and dissemination of results

IPR ownership will be retained by the respective designers/manufacturers (of the CCDs, readout chips and bump-bonding facilities). The goal is to establish the competence for this new type of detector within the existing UK manufacturing base, enabling the manufacturers to offer custom designs for such products in future. The members of this collaboration will have a head start in using this technology in their various scientific experiments. Marconi will contract to offer collaboration members exclusive rights to this technology for one year beyond the development date, after which they will offer unrestricted access to their other customers.

Results will be disseminated by the usual method of presentations at national and international conferences on instrumentation and on the relevant scientific topics, and publications in the scientific literature. In addition, and perhaps most importantly, Marconi will continue to inform their end users when interesting new products become available. In the case of SR detectors, the developments are most likely to make their impact via the manufacturers of X-ray imaging systems who already use CCDs from Marconi and other manufacturers. They will be among the first to grasp the developments resulting from this programme, enabling them in turn to bring exciting new products to market.

Cost breakdown

The cost estimate is approximately £750 K for the CCD development, £1125 K for the readout chip development, £222 K for the bump bonding, £320 K for driver electronics, £297 K for the mechanical R&D programme, £300 K for the Daresbury test facilities, £700 K for four PDRAs, and £140 K for two CASE students with Marconi. The overall cost estimate for the full programme is £3854 K. Contracts will be issued to the commercial partners for the three stages, at intervals of 12-18 months per stage, for four years in total.

BASIC TECHNOLOGY RESEARCH PROGRAMME OUTLINE APPLICATION FORM

Please complete fully all sections of the application form.

To: Dave Godfrey
Technology Support Team (GFN
Research Councils
Polaris House
North Star Avenue
Swindon
Wilts
SN2 1ET

For Office Use Only
Outline No.

Project Details

Proposal Title	The Column Parallel CCD: A Breakthrough in Scientific Imaging
Project Duration	4 years
Research Topic Keywords: e.g. Imaging, Nanotechnology etc	
Imaging systems, Particle detection, Optical and X-ray astronomy, Earth observation, X-ray scattering, Protein crystallography, Digital holography, Electron Microscopy, CCDs	

Project Manager Details

Project Manager	Prof CJS Damerell		
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		E-mail	**c.damerell@rl.ac.uk**

Co-investigators & institutions (include % of time involved in project) [We list FTEs/yr for each group, rather than just the time of the named individual]	Prof N Allinson, UMIST: X-ray scattering [1.5 sy / yr] Prof S Cooper, Oxford U: particle physics [4.6 sy / yr] Dr G Derbyshire, RAL: synchrotron radiation [0.5 sy / yr] Dr A Faruqi, LMB Cambridge: electron microscopy [0.2 sy / yr] Mr M French, RAL: microelectronics [3.0 sy / yr] Dr T Greenshaw, Liverpool U: particle physics / medical imaging [1.6 sy / yr] Dr P Hobson, Brunel U: holographic biological imaging [0.5 sy / yr] Dr A Holland, Leicester U: space science (X-ray) / earth observation [2.5 sy / yr] Dr R Lewis, Daresbury Lab: medical imaging [0.5 sy / yr] Dr D Scutt, Liverpool U: medical imaging [0.3 sy / yr] Dr N Waltham, RAL: space science (optical) / earth observation [1.0 sy / yr] The RAL particle physics group with C Damerell will contribute 5.3 sy / yr Total FTEs / yr = 21.5 plus CASE and other graduate students

Summary of Collaboration (not a pre-requisite for participation in the programme)

Type of Organisation e.g. Industrial, Government Dept.	Organisation Name	Location	Contact Name	Contribution/£

Summary of Project Costs

Total Requested from Research Councils	£3854K	Other Collaborator Contribution	£
Total Industrial Contribution	£	**Total Project Cost**	£3854K