RAL Report
RAL-94-096

hep

Vertex Detectors at Linear Colliders (Present and Future)

C J S Damerell

September 1994

Rutherford Appleton Laboratory Chilton DIDCOT Oxfordshire OX11 0QX

RAL 94-096

Vertex Detectors at Linear Colliders (Present and Future)

C J S Damerell

Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK

After a brief introduction to the general characteristics of pixel-based vertex detectors (as opposed to those using silicon microstrips) we give a general description of the operation of SLD's current CCD-based vertex detector. There follows a description of the design and early prototyping for the SLD upgrade detector, due to be completed during 1995. Finally, we discuss ideas for an extremely powerful vertex detector suggested for use at the future e^+e^- linear collider.

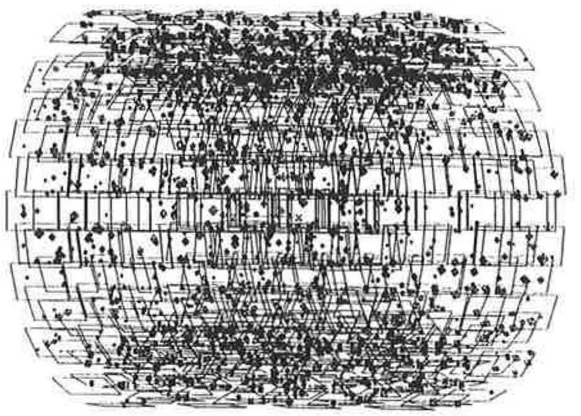

Fig 1. Raw data from one event in SLD. The diamonds represent the charge in the cluster; many of these X-ray hits are single pixel clusters.

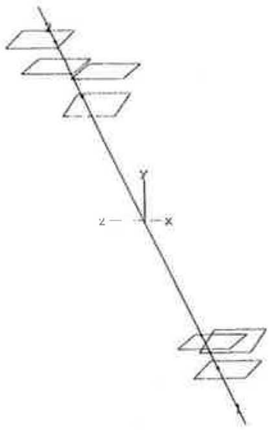

Fig 2. The same event at Fig 1, but showing only the linked hits. This was a particularly simple event of the type $e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-$.

the detector is to function at the small radius required for clean heavy flavour recognition.

However, the saving feature for this physics at the linear collider (both SLC and its future descendant) is the long period between bunch crossings (or between trains of bunch crossings). Here we have a quiet interval of 5-10 ms. While this is not sufficient to completely read out a CCD detector with current technology, it is of the right order of magnitude. As an example, at SLC the present vertex detector can be read out completely over 19 beam crossings. The raw data (Fig 1) looks forbidding, but this consists almost exclusively of X-ray hits (many of them single-pixel clusters) which, being completely uncorrelated in position from barrel to barrel, are easily rejected. The hit density is low compared with the granularity of the detector (120 Mpixels total, 2500 pixels per mm^2) and the hits from the particles of the event can be clearly disentangled by the track finding program (Fig. 2). The same general situation will apply at the next linear collider, but due to advances in CCD technology, the background can be reduced by much faster readout (down from 19 to one train of beam crossings).

A general advantage of working with pixel-based detectors is that since they can be used to provide pictures in the conventional sense, with incident radiation through the spectrum all the way from the near infra-red region to hard X-rays, they have a host of applications outside of particle tracking. There is a very broad body of scientists using CCD detectors. Thus developments from the particle physics community can be of value to other CCD users, and vice versa. The recent development of 'supplementary channel' CCDs [3] is an example where the CCD designers working with the X-ray astronomy community have developed radiation hardening techniques of benefit to all, including commercial X-ray applications such as dentistry.

CCDs are currently manufactured on silicon wafers of 3 or 5 inch diameter, permitting device sizes up to 80 x 80 mm^2. Typical pixel sizes are 20 μm square, so such a CCD would consist of 16 Mpixels. For min-I detectors the active detector thickness is that of the epitaxial silicon (typically 20 μm). Only approximately 5 μm is depleted, but charge from the undepleted substrate is collected rapidly by diffusion. Only when one goes into the highly doped bulk material does one encounter a very short diffusion length and hence no signal collected into the storage pixels. Thus one can consider the detector elements to be more or less cubes of side 20 μm. Being much thinner than microstrip detectors gives CCDs an advantage in tracking precision for oblique tracks. Their intrinsic precision of approximately 5 μm is preserved down to small angles of incidence; this is not achievable in microstrips due to fluctuations in ionisation along the track length as well as the (usually) coarser granularity of the readout in the Z direction.

The signal at the CCD output is deposited on the gate of a MOSFET of the smallest possible dimensions. Refinements in the design of these highly compact devices is leading to excellent responsivity (approximately 4 μV at the output, per electron on the gate). However, such small FETs have very low drive capability. For fast CCD readout, it is therefore desirable to incorporate a second MOSFET on chip to drive the signal to the remote preamplifier.

For optimal noise performance and to minimise the effects of radiation damage [4] it is desirable to run the

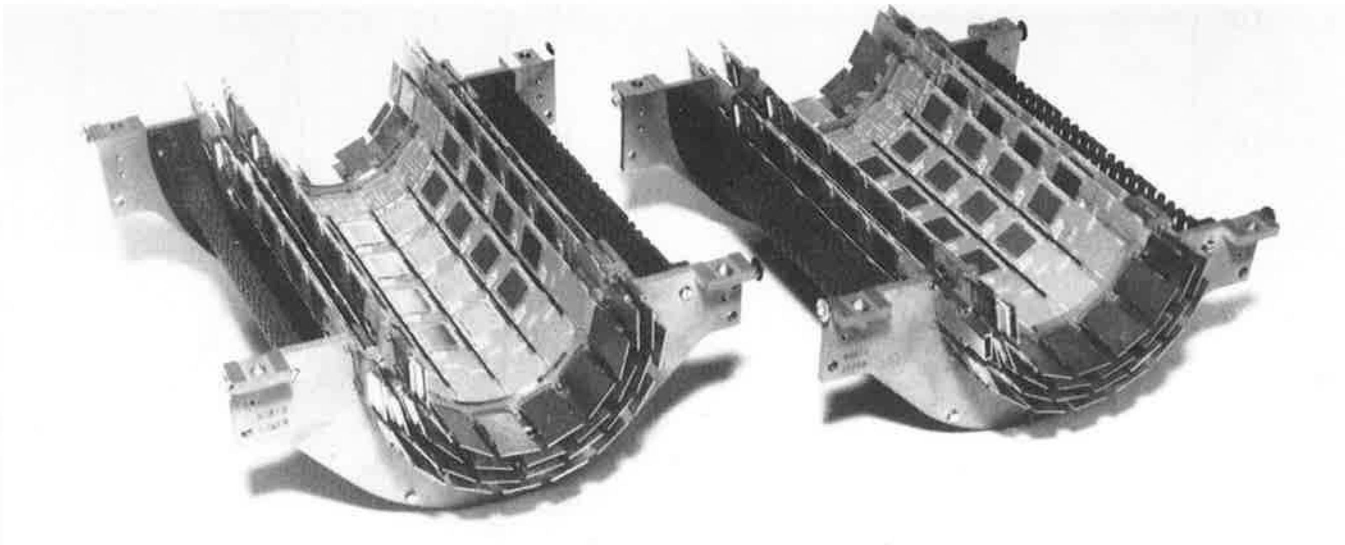

Fig 3. The upper and lower modules of the complete vertex detector. The scale can be judged from the active length of each ladder (96 mm) and radius of Barrel 1 (29 mm).

CCDs at a reduced temperature of approximately 180°K. The detector is therefore housed in a cryostat consisting of an almost massless cylindrical enclosure of expanded polyurethane. It is penetrated by striplines of length approximately 30 cm which connect the ladders to the external electronics. Currently available two stage output circuits are capable of driving these external loads with excellent bandwidth and low noise, permitting clocking rates that were out of the question a few years ago.

The linear collider environment is one which is able to profit from these beautiful CCD developments, and we in particle physics can occasionally contribute to the ongoing progress in CCD detectors, whose capabilities have already transformed experimentation in fields as diverse as laser fusion and astronomy.

2. SLD's Present Vertex Detector

The mechanical construction of this detector has already been briefly described [2]. It was built using 1 cm^2 CCDs of 1980 vintage. These are assembled on both sides of ceramic (alumina) mother boards to form ladders of eight CCDs each. The ladders are assembled into four barrels on radii 29, 33, 37 and 41 mm, 60 ladders in total, as shown in Fig 3. The entire detector consists of 120 Mpixels, read out individually, and data is retained for all pixels forming part of clusters whose total charge exceeds a threshold of a few hundred electrons. The clustering (with a 3 x 3 kernel) is done in real time as the signals are read out synchronously in parallel at a rate of 2 MHz from all 480 CCDs in the detector.

The positions of all the CCDs in the detector were determined by an optical survey, first at the ladder level and then at the barrel level. The beryllium support structure was designed for very repeatable re-assembly (22 parts, each with mating faces lapped to 0.2 μm flatness, and doweled to ± 5 μm). Therefore the CCDs in the assembled 4-barrel detector were expected to be extremely close to the positions established in the four independent barrel surveys. Fine tuning of these positions is done by tracking, and it has been pleasing to find that this procedure has not resulted in any CCDs needing to be moved by more than 20 μm from their surveyed positions.

The detector was built quite rapidly (within two years) after an arduous R&D phase which lasted from 1984 to 1990. The resulting detector has been generally very satisfactory from several points of view.

Firstly, its high granularity and absence of high voltage or any charge multiplication makes it robust with respect to SLC background. Indeed, under conditions where the SLD drift chambers and CRID can not be turned on, the vertex detector reliably records details of the background. In the early phase of SLC, the raw data were useful in understanding these backgrounds. The detector gives a very pictorial representation of the conditions, and one could distinguish between the X-ray hits and the long tracks due to halo particles travelling close to the beam direction, within the plane of the CCDs.

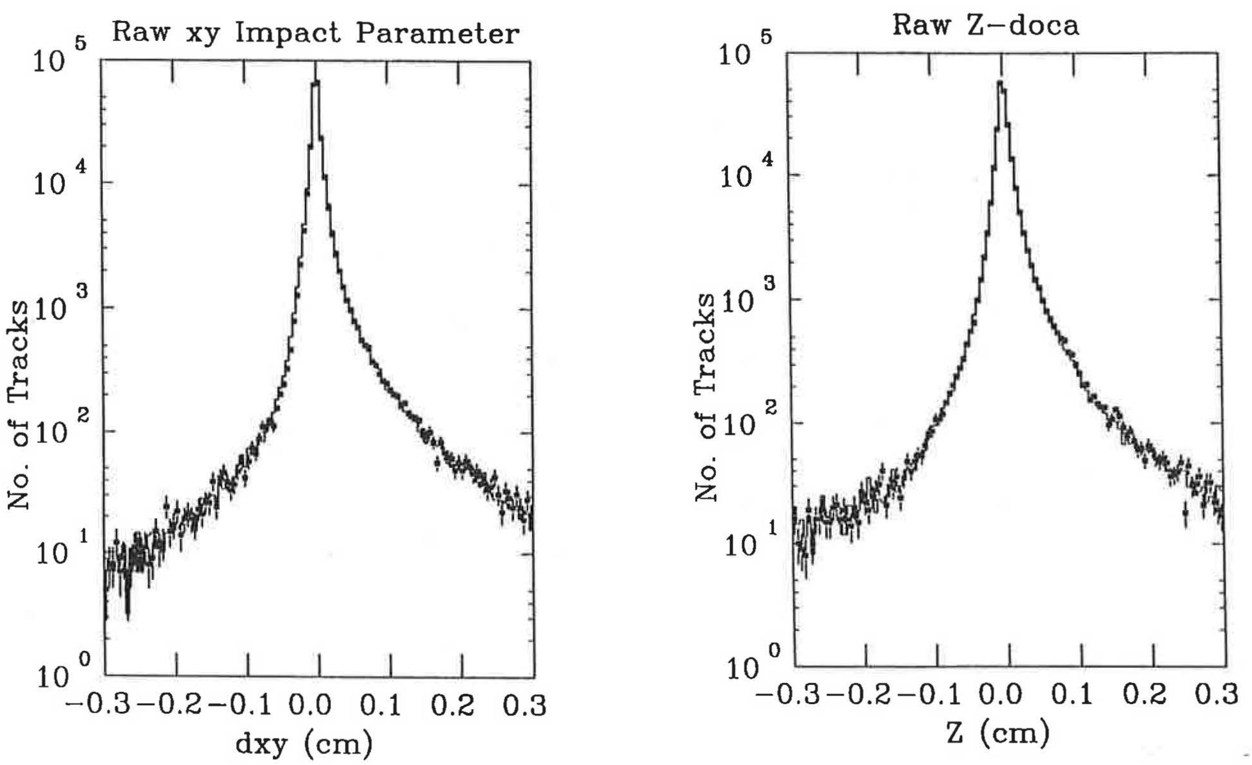

Fig 4. Impact parameter distributions in the *XY* and *RZ* views for tracks from hadronic Z^0decays in SLD. The asymmetry (excess of entries on positive side of plot) is due to tracks from heavy flavour decays.

Secondly, the granularity again results in a negligible level of merged clusters, both between particles in a jet and between these and the X-ray background. This makes for a particularly clean track fitting procedure, and Monte Carlo representation of the detector.

Thirdly, the detector provides at least two space points on every track, though generally with an inadequate lever arm for extrapolation to the interaction region (e.g. two hits at 33 mm and 37 mm radius). This weakness was not present in the original design, but that was based on a 10 mm radius beam-pipe. As concerns grew about SLC backgrounds during the Mark II era, the design radius of the beam-pipe was increased, reaching 25 mm by the end of 1988. In response to this, we lengthened the ladders from five to eight CCDs, but the space available for local electronics limited the number of ladders to 60. This resulted in the rather skimpy coverage shown in Fig 3, where it can be seen that B2 barely covers the gaps in B1, and B4 barely covers the gaps in B3. Also, the radial step of 4 mm between the barrels was much smaller than we would have liked. Building such a closely nested vertex detector was a triumph of mechanical engineering, but it was less than ideal for physics. In order to achieve reasonable impact parameter resolution, we need to rely on the precise track direction given by the Central Drift Chamber (CDC). Particularly in the *RZ* view, this detector is being pushed beyond reasonable limits by this requirement. Even if it could measure these directions perfectly, the extrapolation to the IP would be compromised by multiple scattering in the material between the outer barrel of the vertex detector and the CDC gas volume.

Finally the detector is extremely stable with time. All the differential contraction between dissimilar materials is taken care of by using appropriate adhesives (silicon elastomers) with low glass transition temperatures, and by sliding joints in the mechanical assembly. The detector is now in its third year of operation, has been temperature cycled many times and shows no signs of mechanical drifts, other than overall movements relative to the CDC when the end-doors of the SLD detector are opened and closed.

There is one exception to this positive picture. Electrical connection to each ladder is made by sliding contact micro-connectors (7 fingers at one end and 16 at the other). Since the contact area is necessarily very small, there is the risk of contaminants (e.g. microscopic ceramic chips from the end of the ladder) causing loss of contact when the connectors are pushed on. All contacts

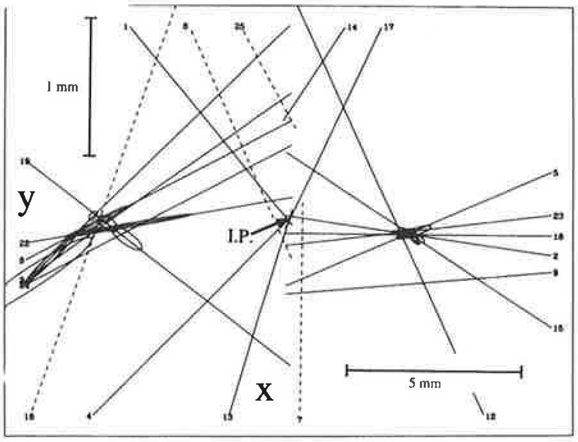

Fig 5. Reconstruction of a typical $b\bar{b}$ event. Note the expanded scale normal to thrust access, the fact that the IP is determined absolutely from neighbouring events, and the partially resolved cascade charm decay associated with the B on the left of the figure.

were good in a final check-out of the two half detectors at RAL, but on assembling these onto the beam-pipe at SLAC, a mishap resulted in a small amount of movement of these connectors, as a result of which contacts on two fingers (out of a total of 1380) were lost. Lacking the appropriate test equipment at SLAC, we sealed the cryostat without being aware of this problem, and have ever since been suffering from the loss of those two ladders. But 58 out of 60 is not too bad, and the really good news is that there has been no further deterioration in two and a half years of running.

The overall technical performance of the detector is best illustrated by plots of the impact parameter distribution in two orthogonal views; these are shown in Fig 4. The first point to note is the excellent agreement between data (points) and Monte Carlo (histogram) over many orders of magnitude, with absolutely no 'fudge factor' in the Monte Carlo. The impact parameter precision may be represented approximately by the form

$$\sigma_{XY} = 13\,\mu\text{m} \oplus \frac{70\,\mu\text{m}}{p\sin^{3/2}\theta}$$

$$\sigma_{RZ} = 35\,\mu\text{m} \oplus \frac{70\,\mu\text{m}}{p\sin^{3/2}\theta}$$

where as usual the $\oplus$ sign indicates adding in quadrature.

This technical performance is as good as any seen at LEP in the $R\phi$ view and much better in RZ. It forms the basis of a healthy SLD physics programme, for example a world class measurement of the B fraction in hadronic Z decays [5]. However, as with the LEP detectors, we are really limited to doing a clean job of B tagging. Once one considers more challenging physics topics, such as a precise measurement of B flight paths (for example, for B_s^0 mixing) or clean recognition of charm vertices (secondary and tertiary) the situation with all existing detectors is marginal. For example, Fig 5 shows a typical SLD event display. The B and $\bar{B}$ decays are clearly well separated from the interaction point, but the suggestion of a cascade charm decay on the left is not convincingly resolved. This also results in a considerable uncertainty as to the B flight path. We need to do better, and fortunately now have the capability to do a great deal better. This forms the topic of the next section.

3. The Upgrade Vertex Detector for SLD

The main problem with the present vertex detector is the inadequate lever arm for extrapolation to the IP, which makes it necessary to rely on the drift chamber to provide directional information of a quality beyond the normal requirements for such a detector. This problem could be solved by considerably increasing the radius of the outer barrel of the vertex detector .

In addition, it would be very desirable to have full 3-hit coverage for all tracks, giving complete stand-alone vertex detector tracking, even in cases (< 1%) of missing hits in one vertex detector barrel. This is particularly desirable because in the dense jets often found in Z^0 decays, there is a small inefficiency in the CDC track finding. It would be extremely useful if one could look at every event with two independent track finding procedures in independent detectors, and thereby tune each of these on the basis of the information from the other system.

In addition, despite lengthening the ladders from 5 to 8 CCDs, the polar angle coverage of the present detector is not adequate. The ability of SLC to produce spin polarised Z^0s makes the ends of the polar angle range particularly valuable for asymmetry measurements, and it is most important to be able to extend the heavy flavour recognition beyond the present limit of around 0.70 in $\cos\theta$.

In addition, the existing vertex detector is really too thick. Each side of each ladder has printed on it a 2-layer circuit covered by a ground plane. This was required in order to bus the signals to the 8 CCDs that are tiled together to cover the length of the ladder. Overall the present

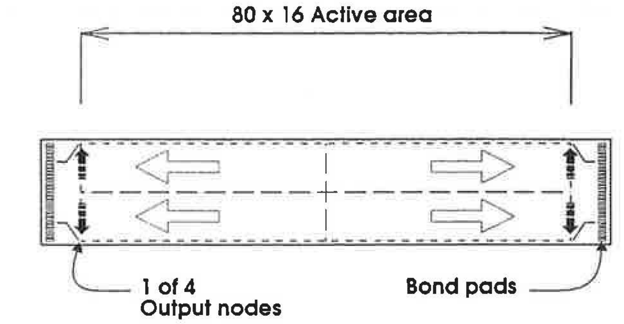

Fig 6. CCD layout for the upgrade detector. Note that the charge is transferred synchronously and in parallel to 4 outputs on the chip. Dimensions are in mm.

detector consists of approximately 1.1% of a radiation length (RL) per barrel.

All these problems can be solved by taking advantage of the advances in CCD technology since 1980. We have now designed a custom CCD (the first for particle physics) which offers us solutions to all the above problems. Firstly the device size (80 x 16 mm^2) is twelve times larger than at present, as shown in Fig 6. The active area comes to within 0.25 mm of the sawn edge of the die along the long edges, and the bond wires are attached only at the short ends. This contrasts with the present detector, where bond wires have to be attached on all four sides of the CCD. This CCD geometry allows us to make a ladder with just two CCDs, one on each side of a thin beryllia mother board, as shown in Fig 7. Because of the favourable bond pad layout, the ladders can be assembled in barrels as shown in Fig 8, where the active areas of adjacent ladders overlap. Thus with 3 barrels we are guaranteed at least 3 hits on a track (whereas the 4 barrels of the present detector guarantee only 2 hits). The radial separation of 20 mm between the first and last hit (compared with as little as 4 mm in the present detector) gives superb extrapolation to the IP. An isometric drawing of the proposed detector is shown in Fig 9. The upgrade detector will give full 3-hit coverage out to $|\cos\theta| = 0.85$.

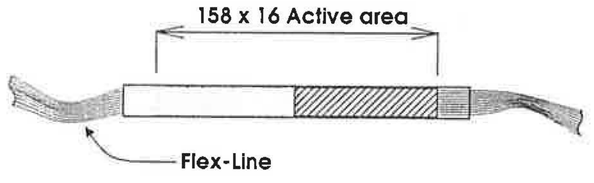

Fig 7. Layout of the 2-CCD ladder for the upgrade detector. Flex-lines are wire bonded to the traces on the motherboard, eliminating the micro-connectors.

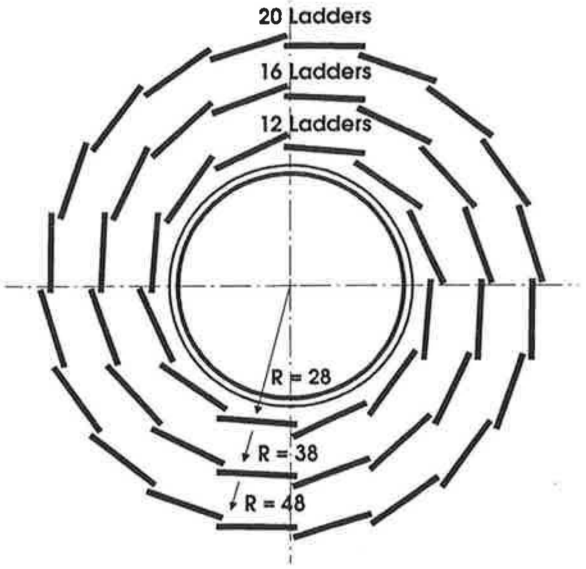

Fig 8. Upgrade detector layout (cross-section). Dimensions are in mm.

The evolution in the size of the detector is illustrated in Fig 10, which shows a 5 inch wafer processed with various commercial CCDs, one of the original 5-CCD motherboards (front right), with behind it a motherboard of the size used in the present detector, and a full scale model of the upgrade detector showing the support shell (to be in beryllium) within which will be housed 2-CCD ladders of 158 mm active length.

Just as important as the improved geometry is the reduced thickness of the detector. The metalisation on the motherboard will consist only of single layer thin film aluminium over half the length (to carry the connections to the remote end of the CCD on that side). Various other improvements (choice of metal, die attach material and method, reduced CCD thickness) allow us to achieve an overall thickness of 0.40% RL per barrel. The resulting performance (to be compared with that quoted for the present detector in Section 2) is

$$\sigma_{XY} = 9\ \mu\text{m} \oplus \frac{29\ \mu\text{m}}{p \sin^{3/2}\theta}$$

$$\sigma_{RZ} = 14\ \mu\text{m} \oplus \frac{29\ \mu\text{m}}{p \sin^{3/2}\theta}$$

The multiple scattering term is much smaller than for any of the currently built or planned LEP vertex detectors. Therefore we should have a considerable advantage for

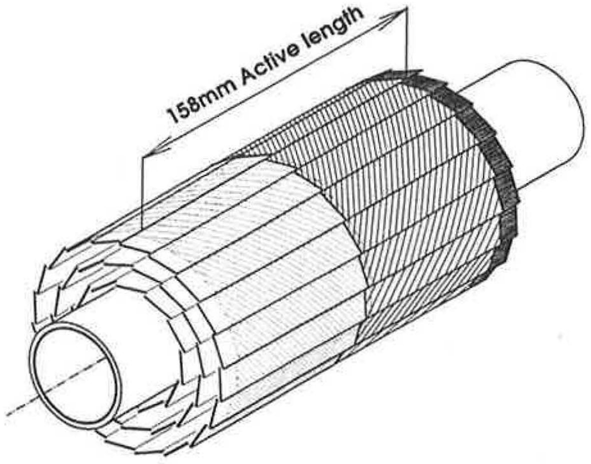

Fig 9. Upgrade detector layout (isometric view)

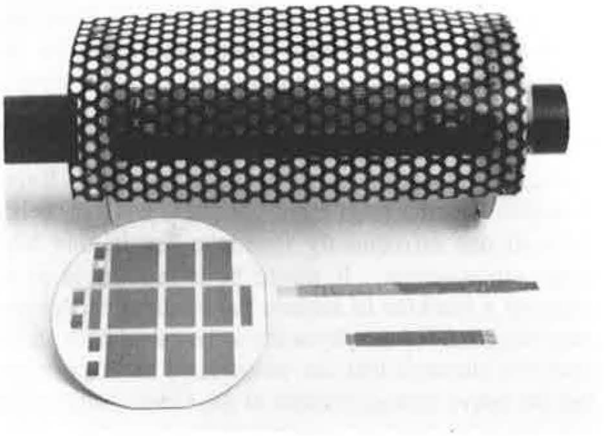

Fig 10. Photograph of model of the upgrade detector, and other items (see text).

the reconstruction of heavy flavour events which do generate a large number of low momentum tracks. More importantly, simulations indicate that the flight path precision achievable with the upgrade detector will permit us to access such important areas of physics as B_s^0 mixing with sensitivity to values of the mixing parameter x_s up to around 20. One could have done even better had it been possible to reduce the beam-pipe radius much below 25 mm. In fact, SLC backgrounds limit us to 23.5 mm, barely any improvement from the present situation. To get really close to the IP we have to wait for the next linear collider, it seems!

The advances in CCD technology have transformed the detector design. It is equally true that advances in other areas permit us to design a far superior system of external electronics. For the present detector, all that could be squeezed into the space available inside the CDC inner barrel were the 480 preamplifier channels south of the IP, and the 60 channels of fast drive electronics on the north side. This then required a plant of some 2500 coax cables linking the local electronics to 8 crates of Fastbus electronics in the penthouse on top of SLD. For the upgrade detector, the entire drive circuitry can be accommodated in the CDC barrel, as well as all the analogue readout through to the A to D conversion. The cable plant is thus reduced to a few power cables plus 48 optic fibres emerging from each end of the CDC barrel. The Fastbus plant shrinks to 3 crates.

The combination of the 2-phase CCD readout register, the 2-stage analogue output circuit and superior external electronics allows much faster clocking of the detector. Already we have tested a pre-production linear CCD of the new design, and have been able to read it out at 10 MHz (5 times faster than in the present detector) with excellent Min-I signals and low noise. This means that despite the larger CCD area per output we shall be able to achieve 3 times cleaner data from this detector than we have now (and are comfortable with) in SLD.

Since the new electronics is so much more compact, we are able to enormously reduce the material all the way down to $|\cos\theta|= 0.9$, the limit for end-cap tracking in SLD. There is consequently a significant reduction in the level of multiple scattering and secondary interactions of particles beyond the angular range covered by the SLD vertex detector and central tracking system.

4. Ideas for a Vertex Detector at the Future Linear Collider

It is generally accepted that there should be only one future linear collider in the world. However, the variety of designs (NLC, JLC, TESLA, CLIC,...) indicates the lack of an internationally agreed proposal at the present time. It is hoped that the situation may evolve over the next two or three years to the point where we do have a single proposal. Indeed, the excellent annual workshops on this topic are making wonderful progress, informally building up the international team which will do the job. However, funding for such a project will not be easy to find, and it may be that a real machine is more than 10 years distant. Why should we then be even talking about the vertex detector for such a machine? Indeed, in the early days of thinking about detectors for SLC, a rapid cycling bubble chamber was considered as a possible vertex detector. Maybe when the next LC is built, a CCD-based detector may sound equally quaint. But I somehow doubt this. The CCD was invented in 1970 [6]. Within four years, with the discovery of charm, it was being considered as a possible high precision tracking detector. Now, 24 years after its invention, the CCD technology has advanced sufficiently to allow us to build a system reasonably matched to the challenging requirements of a collider vertex detector. So the likelihood of a completely new technology blossoming in time for the next LC is not so high. Furthermore, the physics studies for that machine demonstrate the critical importance of clean heavy flavour tagging. Event topologies become even more complex, with $c\bar{c}$ being produced not infrequently from the sea in this high energy environment. It would be irresponsible to be designing a machine to achieve the required energy and luminosity, and for the physicists to be calculating all the wonderful channels that can be accessed and recognised from the heavy flavour content of the events, without the assurance of at least one detector technology that will be capable of disentangling the vertex topologies while taking account of the background associated with that machine design. That this is not a minor issue is demonstrated, as we have pointed out, by the fact that the present generation of LEP/SLC vertex detectors is at best marginal in this respect. We really need a smaller beam-pipe, and a less massive detector with better polar angle and radial coverage than any currently installed. In the case of SLC, the upgrade detector described in the last section will go a long way to satisfying the requirements. However, to completely solve the problem, one really needs to make major progress on another vital parameter, namely the beam-pipe radius.

In the future LC, the collider and detector system are married together as never before. A most critical requirement in achieving the design luminosity, given the nanometer scale of the vertical beam dimensions, is the relative alignment of the opposing quadrupole doublets. This (on present thinking) can only be achieved by housing these inside a robust tube of diameter approximately 1 m which runs right through the detector. The vertex detector, and possibly also the outer tracker, will be located inside this support tube.

At SLC, backgrounds at small radius in the interaction region provide the most sensitive 'barometer' of the state of the machine. Minor imperfections (e.g. small vibrations) in the upstream end of the linac or damping rings can cause beam halo which creates havoc as it swings through the final focus, generating a large amount of synchrotron radiation. At the future LC, synchrotron radiation can probably be reduced to a negligible level by a combination of arc collimators and a final focus design which allows the radiation generated by one bunch to pass out through the downstream quadrupoles, without impinging on any material until it is well beyond the detector [7]. As previously mentioned, incoherent pair background then becomes the main factor in determining the smallest practical beam-pipe radius. Here, the electrons created can be confined by an intense solenoid field of around 4 Tesla. With designs currently being considered for the final focus at the next LC, such a solenoid field results in comfortable backgrounds in a CCD-based vertex detector even with the inner barrel radius set at 8 mm [8]. Simulations indicate that a 3-barrel CCD detector can achieve clean stand-alone tracking with hit densities as high as one per mm^2 on the inner barrel (pixel occupancy approximately 3 x 10^{-3}). This condition is comfortably satisfied with the design under discussion. In addition to the pair background, the positrons spiralling away from the interaction region have a high probability of hitting the face of the opposing quadrupole or masks, generating 500 KeV gamma rays which can then shine back, infecting the detector. Shielding against these also becomes more effective as the magnetic field is increased, since the aperture required for the pair particles entering the masking volume can be reduced. One should not attempt to be too precise with these limits, since it is obvious that major developments in CCD technology will transform our capability over the next ten years, particularly in the area of node capacitance (and hence responsivity and signal-to-noise ratio) and radiation resistance (variations on the theme of supplementary channels). What is clear is that CCD readout speed (for a given noise performance) will continue to improve, and there will be no problem to read out the two CCDs on a ladder from just two nodes at each end of the ladder. This means we shall no longer need *any* electrical connections on the motherboard, which can as well be fabricated out of beryllium as is the rest of the support structure. The CCD can then be thinned down to approximately 20 μm, using the back-contact procedure now being pioneered for astronomical applications. Thus the barrel thickness can be reduced from 0.40% RL (SLD upgrade) to 0.11%.

Interestingly, this combination of unprecedentedly small beam-pipe and low mass detector will (for the first time) apply pressure on the CCD design as regards its intrinsic spatial resolution. Until now, the 'standard value' of 4-5 μm in both dimensions has contributed negligibly to the impact parameter precision of most tracks. At the future LC, with the above mentioned detector design parameters, this will no longer be true. Furthermore as shown in [8], the confusion between specifically *charm* decay products and their parent vertices (primary or B) will require yet higher detector precision in order to resolve the ambiguities efficiently. To this end, it is suggested that we should develop the CCD design to achieve approximately 1 μm spatial resolution for min-I tracks. This should in fact be fairly straightforward. Already, with large signal charge and defocused images, CCDs yield approximately 0.1 μm resolution in star tracking systems. For min-I particles, one can increase the signal with thicker epitaxial material (***without*** increasing the depletion depth) and one can achieve the equivalent of a defocused image by having the majority of the signal collected by diffusion rather than drift; this is automatically achieved with such a structure. Prior to the construction of a vertex detector for the next LC, it would be wise to build some CCDs according to these principles (as variants of those now being processed for the SLD upgrade) and measure and tune the spatial resolution in a test beam.

Incidentally, the other essential requirement, a support structure stable at the sub-micron level, has (we believe) already been achieved with the SLD design, but the evidence is indirect (coming from similarly engineered structures used for space-based astronomical systems). This has to be proved experimentally for a collider detector.

It seems to me unlikely that the combination of advantages of CCD detectors (unique, precise space points for each hit, high granularity, low mass, low power dissipation, good radiation resistance) will emerge on the timescale of the next LC from some currently unborn technology. The most dramatic change beyond the evolutionary developments outlined above may possibly be the development of GaAs CCDs to the point where they become available in the size we are discussing for the SLD upgrade, but this is far from certain.

The SLD upgrade detector will use the first fully customised CCDs for particle physics, and will address most of the issues relevant to the linear collider environment at higher energy. The compact electronics and very few external connections are well matched to the need to put the detector inside the final focus support tube and keep it mechanically decoupled from the main detector. The stand-alone tracking capability means that precise linking to the external tracker is no longer an issue. The low power dissipation means that the combination of an almost massless cryostat and some slim cryopipes bringing in a gentle flow of nitrogen cooling gas is all that is required. This will cause no problems of mechanical vibration, as would be disastrous in the final focus on the future LC. The local electronics can be mounted mechanically independently, but its water cooling at a very modest flow rate (total dissipation approximately 200 W) will also be relatively benign from the point of view of driving mechanical vibrations.

In conclusion, the SLD upgrade detector is the ideal stepping stone to the future LC. Once it is installed, running and fully understood, we should be in a good position to propose a modest R&D program to develop the CCDs and ladders for a detector that will provide the future LC with the tool it needs in order to access the full range of physics to be explored at that machine.

Acknowledgements

The work on CCD-based vertex detectors has expanded from small beginnings to an international effort involving many groups. It is a privilege to be associated with the infusion of new ideas and enthusiasm. I wish to acknowledge the ongoing contribution of many excellent colleagues to the present successes and to the ideas for future developments in this area. Groups which are currently actively participating in the work come from Brunel University, the EEV Company (which is designing and manufacturing the CCDs), University of Massachusetts, MIT, University of Oregon, RAL, SLAC and Yale University.

References

1. ACCMOR Collaboration, *Physics Letters B* **236** (1990) 495. This is one of many papers on charm physics using CCDs for vertex reconstruction. Here we measured the lifetime of the Ξ_c^0 baryon, at 0.8 x 10^{-13} s.
2. C J S Damerell et al, *Proc XXVI Conf on High Energy Physics, Dallas* (1992) 1862.
3. A D Holland et al, *IEEE Trans Nucl Sci* **38** (1991) 1663.
4. M S Robbins, *PhD Thesis, Brunel University* (1992).
5. SLD Collaboration, *SLAC-PUB* 5972 (1992).
6. W S Boyle and G E Smith, *Bell Syst Tech J* **49** (1970) 587.
7. JLC Group, *KEK Report* 92-16 (1992) 105.
8. C K Bowdery and C J S Damerell, *Physics and Experiments with e^+e^- Linear Colliders* (1993) 773 (World Scientific).