A CCD Vertex Detector for the future Linear Collider

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Abstract

The future e^+e^- linear collider (LC) will be crucial to developing an understanding of the open questions in particle physics, and an important tool in the investigations at the LC will be the efficient identification of heavy quarks. Experiments must therefore be equipped with high precision, low mass vertex detectors (VXDs). This paper describes progress in the design and development of a CCD based VXD for the LC. In particular, the results of simulations of the high-speed readout necessary if the LC is of the TESLA type are presented, as are first studies of self-supporting CCD ladders, which allow a further reduction in the already small material budget of the VXD.

I. INTRODUCTION

Despite the enormous success of the Standard Model (SM), which provides a unified description of the electromagnetic and weak forces, many important questions remain unanswered in particle physics. There is as yet no conclusive evidence that mass is generated via the Higgs mechanism, as implied by the SM, though there has recently been some suggestion that the Higgs boson may be visible in the combined data of the LEP experiments at a mass of about 115 GeV. Current electroweak data imply that, if the Higgs mechanism is indeed responsible for particle masses, the Higgs boson must have a mass $m_H < 170$ GeV (95% CL) [1].

Concepts beyond those in the SM must be introduced if attempts are made to unify all the forces of nature. Ensuring that the Higgs boson does not acquire a radiatively generated mass close to the energy at which unification occurs requires that new strong forces be invoked, or that a new symmetry between fermions and bosons, supersymmetry (SUSY), be introduced. It is thought likely that evidence for one or the other of these will be observable in interactions at a centre-of-mass (CoM) energy around, or in the case of SUSY probably well below, $\sqrt{s} = 1$ TeV. The last days of LEP running, the upgraded TeVatron, or the LHC may produce this evidence, but even if this is the case it appears that detailed investigations will require a LC operating in the 0.3…1 TeV range [2].

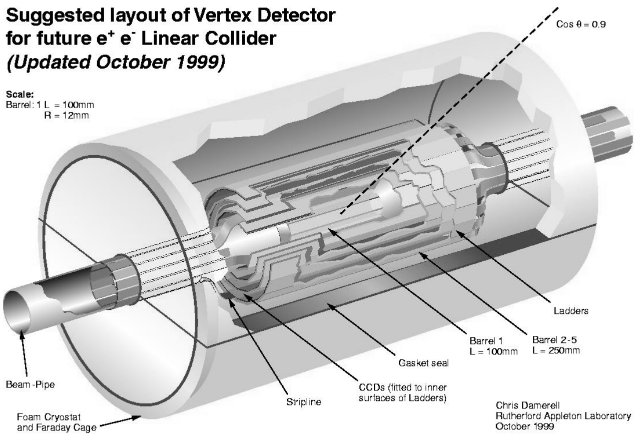

Figure 1: A CCD based VXD for the future LC.

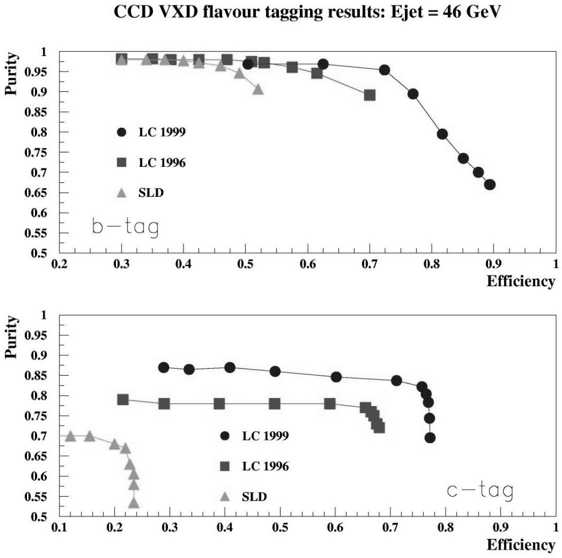

Figure 2: The efficiency and purity with which b quark (upper figure) and c quark (lower figure) jets can be identified using the CCD based VXD considered here compared with the results obtained using the SLC detector and an earlier future LC VXD design.

One of the essential experimental tools at the LC will be efficient and accurate quark flavour identification. As an example, if the Higgs boson is discovered, measurement of the branching ratios for its decay to c and b quarks will determine whether it is the particle expected in the SM, or whether it displays the enhanced decay rate to down type quarks typical of SUSY theories. It is thus essential that the detector at the LC be able to identify the ~ 100 μm impact parameters that result from the decay of charmed particles. Identifying b quarks is a less demanding task due to the longer b lifetime. This requires the measurement of several points on the tracks of charged particles with an accuracy of around 5 μm or better as close to the production vertex as is possible; a high precision vertex detector (VXD) is essential. Further, as the momenta of the particles to be measured are typically ~ 1 GeV, they suffer significant multiple scattering in material and the VXD must present as little material as is possible to

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traversing particles. A CCD based VXD with 20 x 20 μm^2 pixels, as illustrated in figure 1, satisfies both these requirements. In this detector, CCDs of thickness 20 μm are attached to 250 μm thick beryllium support beams, giving a thickness per layer of 0.11% X_0. For $|\cos\theta| < 0.9$, 5 hits are recorded on each track and at least 2 hits are recorded on tracks for which $|\cos\theta| < 0.96$. The point measurement precision is 3.5 μm in both the transverse and longitudinal (z) directions, as achieved by the CCD based SLD VXD [3].

The flavour identification performance attainable with the help of such a VXD is illustrated in figure 2. Shown are the efficiency and purity with which samples of b and c quark jets may be identified using topological vertex finding [4] and secondary vertex mass algorithms developed by the SLD collaboration [5]. The CCD based VXD results were obtained using simulations of the above VXD design incorporated into the detector proposed for the Tera-Electronvolt Superconducting Linear Accelerator (TESLA) [3]. The physics process simulated was $e^+e^- \rightarrow q\bar{q}$ at $\sqrt{s} = m_Z$ and the results are for the angular region $|\cos\theta| < 0.71$.

The remainder of this paper investigates whether a VXD such as the above can satisfy the constraints imposed on it by the LC environment, in particular, whether the readout speed demanded by TESLA may be achieved. The results of recent studies on methods of further reducing the amount of material in a CCD based VXD are also presented.

II. FAST READOUT OF A CCD BASED VXD

A. Background in the VXD at a LC

Worldwide, there are currently two approaches to constructing the next generation LC. That pursued at the Stanford Linear Accelerator Centre and in Japan foresees using copper cavities driven at a frequency of 11.5 GHz to accelerate the particles in the Next LC (NLC) or Japanese LC (JLC), an approach familiar from the Stanford Linear Collider (SLC). The DESY laboratory in Hamburg, Germany proposes to use superconducting cavities operated at a frequency of 1.3 GHz in the TESLA collider. The two-beam acceleration scheme CLIC, under study at CERN, is probably more appropriate for a later and higher energy LC.

Table 1
Linear collider parameters

	NLC/JLC	TESLA	CLIC
√s (TeV)	0.3…1.0	0.09…0.8	1…5
$\mathcal{L}$ ($\times 10^{34}$ cm^{-2} s^{-1})	0.5…3.4	3.4…5.0	11…15
Rep. rate (Hz)	120	5…3	150…50
Bunches/pulse	95…190	2820…4500	154
Bunch sep. (ns)	1.4…2.8	337…189	0.7

The designers of the detectors for these machines must ensure they satisfy the requirements imposed on them by the machine environment. Of particular note here are the different time structures with which the colliding electron and positron bunches are delivered, as outlined in Table 1.

The electromagnetic fields associated with these bunches are so intense that photons radiated from the particles in one bunch may produce electron-positron pairs in the field of the other. These pair-produced particles spiral in the 4 Tesla solenoidal magnetic field of the detector, but some of them cross, and produce signals in, the VXD. If the number of these hits is large, the probability that one of them is incorrectly associated with the track of a particle produced in an e^+e^- interaction becomes significant, making the measurement of these tracks inaccurate and efficient flavour identification impossible. The number of hits per bunch crossing (BC) caused by e^+e^- pairs in the inner layer of the VXD is shown in Table 2, for the minimum radii expected to be tolerable at each machine.

Table 2
Hits in the VXD resulting from e^+e^- pair production.

	NLC	TESLA	CLIC
√s (TeV)	0.5	0.8	3
Radius (cm)	1.2	1.5	3.0
Hits (mm^{-2} BC^{-1})	0.1	0.05	0.005
Hits (mm^{-2} BT^{-1})	9.5	225	0.8

These figures are for a length along the beam, or z, axis of about ±5 cm, beyond which the number of pairs rises, limiting the possible length of the VXD.

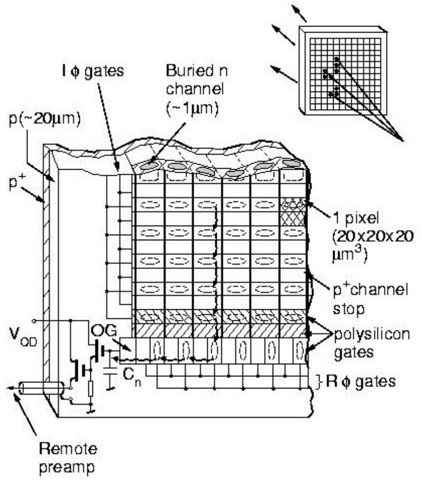

Figure 3: Tracks crossing the pixels of a CCD (inset top right) and the readout of the charge deposited by those tracks down the I register and across the R register (main picture).

In order to ensure tracks are not confused by random hits, a sensible rule-of-thumb is that less than around 1% of pixels should have been traversed by a particle. There are 2500 pixels per mm^2, so the number of hits per bunch train (BT) at the NLC allows readout in the long interval between BTs without exceeding this limit. At TESLA however, the CCDs must be readout around ten times per BT to keep the occupancy at the 1% level. This is not feasible with conventional CCDs, in which the charge deposited in the pixels is moved down the image (I) register then across the readout (R) register to the external electronics, as illustrated in figure 3.

B. Column Parallel CCD Readout

The solution to the above problem proposed by the Linear Collider Flavour Identification (LCFI) collaboration is to dispense completely with the R register and read out each column of the I register into its own electronics chain. This "column-parallel" readout scheme is illustrated schematically in figure 4. Reading out the 10 cm, or 5000 pixel, long inner CCDs from both ends ten times during the 4500 x 189 ns TESLA BT requires that the time to read out each pixel be about 20 ns, i.e. that the I register readout frequency be about 50 MHz.

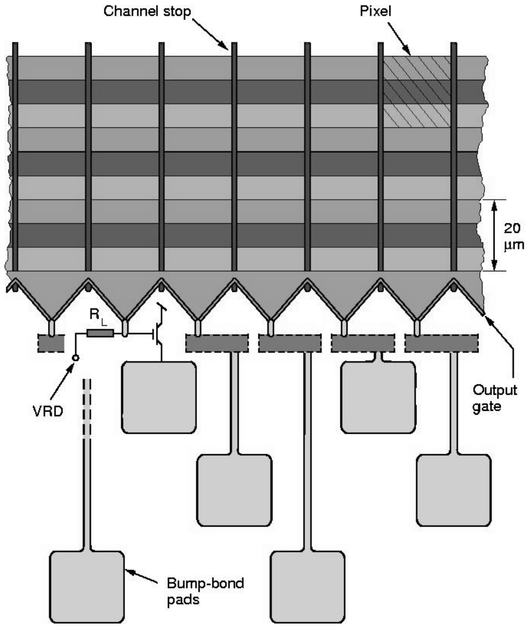

Figure 4: Three-phase column-parallel CCD readout; each column of the I register has its own readout chain.

Efficient column-parallel readout requires that sufficiently well defined clock signals be produced on the gates which drive the I register over the entire surface of the CCD. Is this possible at a frequency of 50 MHz? In order to examine this question, SPICE simulations were performed of the circuit, shown in figure 5, which is equivalent to the column-parallel CCD of figure 4. A CCD length of 10 cm and a width of 13 mm were assumed, the dimensions necessary for the innermost layer of the detector illustrated in figure 1. The values chosen for the I gate to substrate capacitance, $C_S = 3.3$ pF mm^{-2}, and the inter-gate capacitance, $C_I = 2.5$ pF mm^{-2}, are reasonable for a CCD in which both the buried channel and the channel stop regions are depleted, as would be the case with a positive gate bias throughout the full clock cycle. The polysilicon gate resistance was assumed to be $R_G = 3$ kΩ mm^{-1}, the aluminium clock bus line resistance to be $R_B = 0.5$ Ω mm^{-1} and both the driver output impedance, R_D, and the driver to clock bus inductance, L_D, were initially assumed to be negligible. Square clock pulses with a swing of 1 V and frequency of 50 MHz were supplied at the corners of the CCD at z = 0 and 10 cm. (The inset in figure 5 shows the definition of the coordinate scheme and the location of the drivers.) As is apparent from figure 6, with these parameters, in the centre of the CCD, even at its ends, the pulses are degraded to an extent that would prohibit efficient charge transfer down the I register.

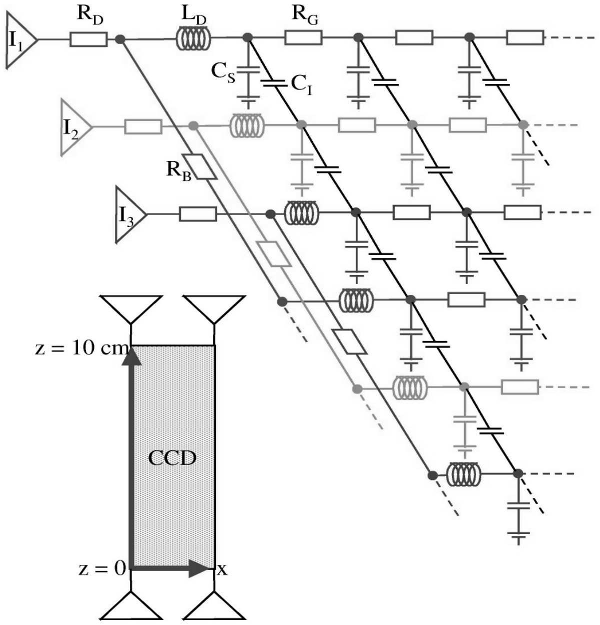

Figure 5: Circuit used in SPICE simulation of 3-phase column-parallel CCD readout together with schematic illustration of location of drivers and definition of coordinate scheme used in text (inset lower left).

The solution to this problem is to reduce the resistance of the gates by overlaying them with 3 µm wide aluminium strips. Doing this leads to acceptable performance at z = 0 and 10 cm for the full width of the CCD, but the performance in the centre of the CCD at z = 5 cm is still unacceptable. Reducing the resistance of the bus lines, by increasing the thickness of the aluminium, leads to acceptable performance across the whole surface of the CCD, as is illustrated in figure 7. This conclusion is not affected by adding an inductance $L_D = 200$ pH between the drivers and the CCD.

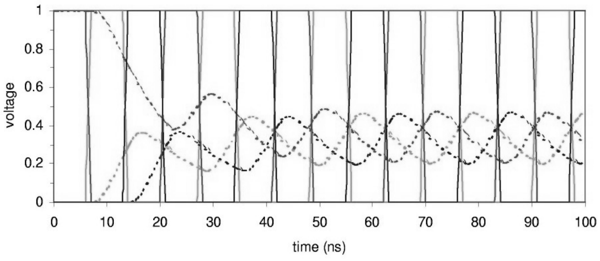

Figure 6: Clock pulses for all 3 phases at the corners of the CCD at z = 0 (solid lines) and at the centre for the same z values (dotted lines).

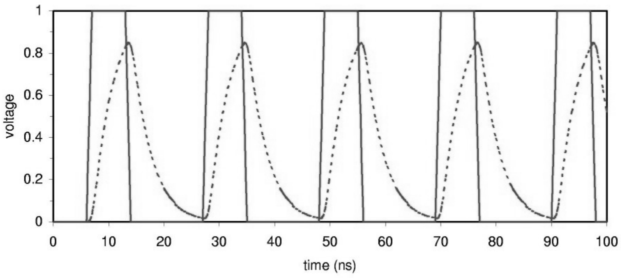

Figure 7: Clock pulses for 1 phase at the corners of the CCD at z = 0 (solid line) and at the centre of the CCD for z = 5 cm (dotted line).

C. *Use of Sinusoidal Drive Pulses*

An attractive further development of the column-parallel readout scheme examined above is to move to a 2-phase gate structure and use sinusoidal clock wave-forms. This results in the lowest possible driver frequency spectrum and reduces the peak current demands on the drivers. The balanced anti-phase wave-forms should also produce minimal cross-talk at the CCD outputs. Results from a SPICE simulation of this arrangement are shown in figure 8.

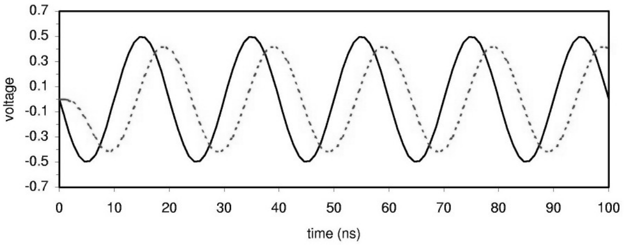

Figure 8: Clock pulses for 1 phase of a 2-phase CCD with sinusoidal clock pulses at the corners of the CCD at z = 0 (solid line) and at the centre of the CCD for z = 5 cm (dotted line).

The wave-forms in the centre of the CCD are perfectly adequate for efficient operation and this conclusion remains unchanged for a range of not unrealistic choices of capacitances, inductances and resistances. Using 1 V peak-to-peak clock pulses results in a total power dissipation of about 1 W per CCD. If the TESLA duty cycle of 1:200 is exploited, this reduces to a mean power of about 50 mW per CCD and results in a total power consumption for the VXD of a few Watts. Thus, adequate cooling can be achieved with a gentle gas flow, obviating the need for liquid or other cooling schemes, which are inevitably associated with increases in the thickness of the VXD and a concomitant loss of performance.

III. REDUCING THE VXD MATERIAL BUDGET

A. *More Physics Challenges*

Accurate measurement of the axial and vector coupling constants of the heavy quarks, the reduction of combinatorial background problems in the study of SUSY Higgs bosons in complex events, e.g. $e^+e^- \to t\bar{t} \to WWh \to (\mu\bar{\nu})(c\bar{b})(b\bar{b})$, and the measurement of the tri-linear gauge coupling constants are some of the topics that could benefit from the ability not only to identify b and c quark jets, but also to distinguish between b and $\bar{b}$ jets and c and $\bar{c}$ jets. In the case of jets like that illustrated schematically on the left of figure 9, this may be achieved by correctly identifying which particles came from the primary, secondary and tertiary vertices and measuring their charges; in this decay chain, the positive charge of the pion coming from the secondary vertex reveals that a B^+, and hence $\bar{b}$, was produced. The charge of the b quark in the jet on the right of figure 9 cannot be deduced unless the LC detector is capable of identifying that the positively charged particle emerging from the tertiary vertex is a kaon, not a pion.

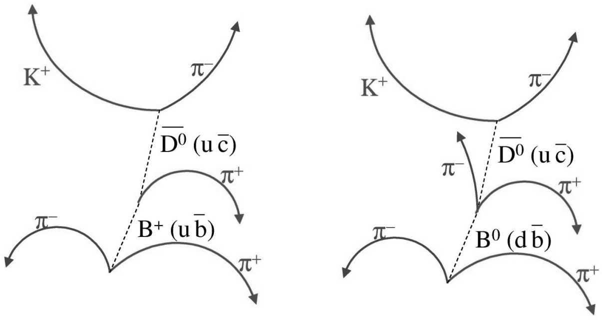

Figure 9: A $\bar{b}$, as opposed to b, jet which may be distinguished by identifying the charges of the particles associated with the secondary and tertiary vertices (left) and a $\bar{b}$ jet which can only be identified if k/π separation is also possible (right).

The task of the VXD in the above is to correctly associate all the particles in a jet, including those with low momenta, with the primary, tertiary or secondary vertices. This places even more stringent requirements than flavour identification on the precision of the VXD. In particular, as the association must be correct for the lowest momentum particles, reducing the amount of material in the VXD to an absolute minimum becomes essential.

B. *Self-Supporting CCDs*

In order to further reduce the material budget below the 0.11% X_0 per layer of the current VXD design, investigations are underway of the possibility of removing the beryllium substrate used to support the CCDs. The idea is that the CCD ladders be kept under sufficient tension for them to be self-supporting. The worry is of course that such an assembly may not achieve the necessary mechanical stability. In order to investigate this, a test rig was constructed as illustrated schematically in figure 10. This is initially being used to examine the behaviour of 90 μm thick glass sheets, of dimensions similar to those of the CCDs, glued together to form a “glass CCD” ladder. The ladder is attached to ceramic “ladder” blocks at its ends, which are free to move in the longitudinal direction only over the “annulus” blocks. Springs allow a variable tensioning force to be applied to the ladder.

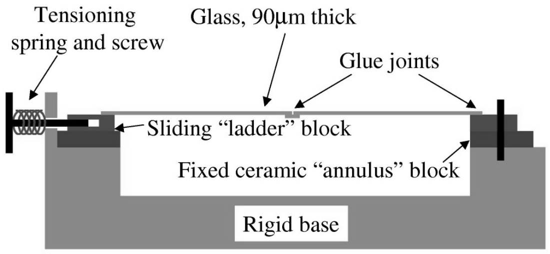

Figure 10: Test rig for examining mechanical stability of self-supporting "glass CCD" ladders.

In order to quantify the stability of the unsupported ladders, their position is measured, they are disturbed and their position is re-measured. This is repeated many times and the root mean square variation of the position of the centre of the ladder determined. This is studied as a function of the applied tension. First results, shown in figure 11, are encouraging. It appears that a tension of around 5 N is sufficient to keep the position of the unsupported ladder stable at the 5 μm level, adequate for the required track measurement precision.

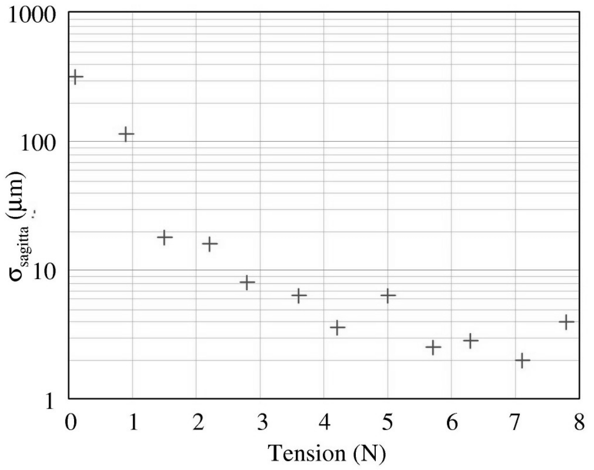

Figure 11: Root mean square position of centre of "glass CCD" ladder as function of applied tension.

These tests will be repeated firstly with silicon of varying thickness and then with CCD ladders.

IV. SUMMARY

It has been shown that a CCD based VXD can provide the flavour identification necessary to the successful completion of the physics programme at a future LC. Development of techniques that will allow readout fast enough to enable CCDs to be used at TESLA is underway. First studies of this "column-parallel" approach suggest that the necessary readout speed is achievable. In this context, the use of sinusoidal drive pulses looks to be worthy of further investigation. Power consumption levels are such that gas cooling is adequate. Conventional readout, albeit running at high frequency, will suffice for the NLC and JLC.

A further problem posed by the LC environment is the dose of approximately 10^9 1 MeV equivalent neutrons per year per cm^2 that simulations suggest the CCDs will receive. Measurements of the effects of this dose on CCDs, particularly those with novel readout schemes, and studies of ways in which those effects can be ameliorated are badly needed and will be undertaken by the LCFI group.

A promising approach to the further reduction of the material in the VXD is under investigation. First studies with ladders made of thin glass sheets, to be repeated with silicon and then CCD ladders, suggest that the use of self-supporting CCDs may be feasible and result in a reduction of the thickness of each layer of the VXD to about 0.06% X_0, enhancing significantly the performance of the VXD for low momentum particles.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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