Vertex Detectors for the Future Linear Collider

James E. Brau
Physics Department, University of Oregon,
Eugene, OR 97403-1274, USA

Abstract. The physics opportunities of a future Linear Collider demand the best possible vertex detection. Research and development on CCDs, hybrid active pixels, and monolithic active pixels promise to improve the state of the art and provide an excellent slate of options for vertexing.

INTRODUCTION

Recent experiments have benefited enormously from investments in excellent vertex detectors. An important lesson has been the immense value of a pixelated detector, which has enable SLD to match many of the physics measurements at LEP with a small fraction of the data. The physics goals of the next Linear Collider[1] will also demand optimal vertex detection. The physics signals are rich in secondary vertices, and event rates are limited, demanding highly pure and efficient tagging.

Physics processes requiring vertex detection are numerous. [1] Some are the Higgs branching ratios, SUSY Higgs searches such as A$\rightarrow$ $\tau^+\tau^-$, searches for staus, top studies, improved measurement of W pairs, Z$'$ studies such as τ polarization, and Z pole physics. Some processes will involve several heavy quark decays, complicating the reconstruction, and increasing the demand for pixelated detectors. The physics will require highly efficient and pure b and c tagging, including tertiary vertex reconstruction, and charge tagging, for example $b/\overline{b}$ discrimination. Optimal performance calls for point resolutions better than 4 μm, ladder thickness under $0.2\% X_0$, inner layers within 2 or 3 cm of the interaction point, and good central tracking linked to the vertex detector. The accelerator time structure and radiation environment will constrain the design, and must be carefully considered.

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1) In this paper, we use interchangeably the designation future Linear Collider and next Linear Collider to refer generically to the multi-hundred GeV e^+e^- linear collider, referring to all of the proposed approaches: NLC, JLC, and TESLA.

THE FIRST LINEAR COLLIDER VERTEX DETECTOR

The pixel CCD vertex detector was developed at the SLC. The SLD vertex detector, VXD3, [2] comprised 307 million pixels on 96 detectors, and achieved 3.8 μm point resolution throughout this large system. With such exceptional precision, extremely pure and efficient flavor tagging at the Z-pole was possible: 60% b tagging efficiency with >98% purity, and c tagging efficiency of better than 20% with 60% purity. SLD also achieved exceptional charge separation between b and $\bar{b}$. The value of the pixel detector has been clearly established, even in the relatively clean environment of the SLC, where the hit occupancy in VXD3 was about 10^{-4}.

The main weakness of the CCD approach to vertex detection is the slow readout speed, and the radiation sensitivity. The speed issue can be managed at the linear collider, as SLD demonstrated. However, for the TESLA time structure, new readout techniques need to be developed (see below). CCDs are expected to withstand the future linear collider environment, but for assurance, CCDs with engineered rad-hard enhancements are foreseen. [3]

Despite the established performance of the CCD vertex detector, active pixels do provide interesting alternatives. They can be inherently less sensitive to radiation damage (hence the interest in using them at the LHC), but generally have been less precise with more material leading to multiple scattering. As described below, efforts are underway to close the gap between the demonstrated CCD performance and the state of the art in active pixels.

RESEARCH AND DEVELOPMENT

Research and development is progressing in several areas, including simulation studies and technology development. A vigorous effort on all of these is the best insurance for an optimal capability at the next Linear Collider.

Simulation Studies

The performance proposed for the next Linear Collider improves significantly on the already demonstrated performance of the SLD vertex detector. [2] Figure 1 compares the impact parameter performance with CCD vertex detectors considered for the next Linear Collider. The variation in performance as a function of the parameters (inner radius and hit resolution) is smaller than the significant improvement over the already exceptional performance of the SLD vertex detector.

The central tracking contributes in important ways to the performance of the vertex detector. This is clear since the momentum resolution of the vertex detector is limited and the impact parameter performance ultimately depends on the momentum resolution and the accuracy of the projection of the track inward to the beamline, being limited by the precision on the curvature. Other parameters which may improve the vertex detector performance include the hit resolution, the

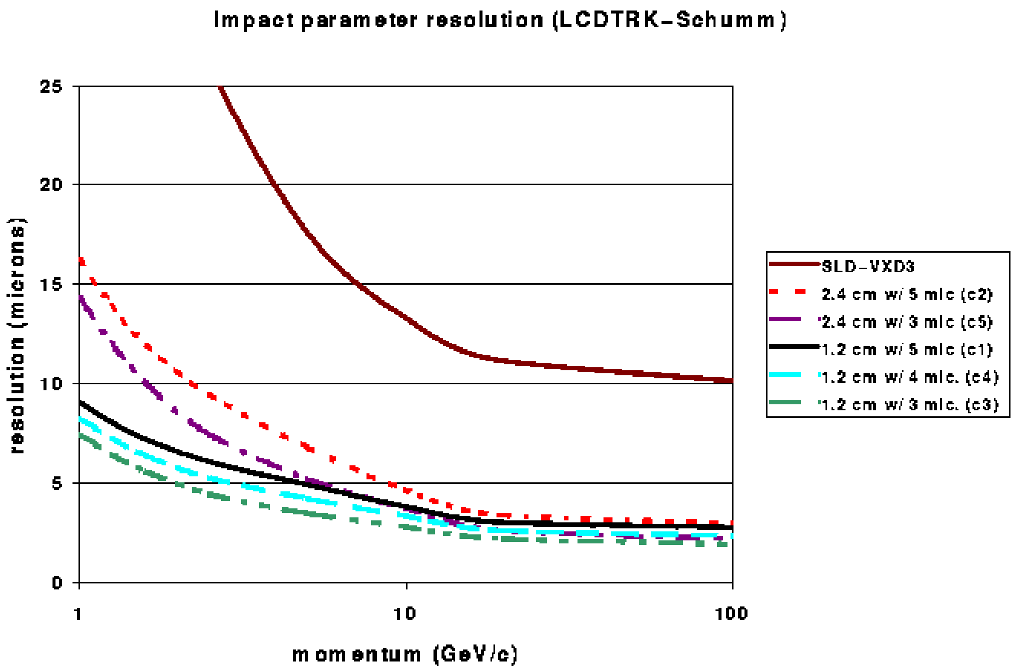

FIGURE 1. Vertex detector impact parameter resolution for several design choices: from top to bottom at low momentum a.) SLD-VXD3, b.-c.) 2.4 cm inner radius with 5 μm and 3 μm resolution, d.-f.) 1.2 cm inner radius with 5 μm, 4 μm, and 3 μm resolution.

beampipe radius (and consequently the inner radius of the vertex detector), the outward radial extent, and the thickness of the layers of the vertex detector. The importance of each of these has been studied, [4] with the emphasis on pushing to more aggressive choices to see how well they improve the performance. These studies [4] conclude that the outer radial extent and the thickness of the layers provide little improvement when the outer extent is increased from 6 cm to 11 cm, and the thickness is reduced 50% from 0.12% X_0, an already optimistic thickness. On the otherhand, significant improvement can result from further improvement in hit resolution. Improvement can also be achieved with a reduction of the beampipe radius, although improvement increases slowly with radii smaller than 1 cm, and appears only at low momentum.

Impact parameter resolution is a useful measure of performance, but flavor tagging performance reveals more clearly the potential impact on physics. Flavor tagging can improve significantly when the inner radius of the vertex detector drops is reduced from 2.4 cm to 1.2 cm [5] as shown in figure 2. These results are consistent with another study of the importance of the inner radius of the vertex detector. [6] Achieving this exceptional separation relies on the topological vertex reconstruction developed for SLD and exploiting the pixelated vertex detector. [7] In both of these studies, the charm tagging is particularly sensitive to the inner radius.

In yet another study of jet flavor tagging, based on the latest TESLA geometry, and employing a neural net analysis of the topological vertex reconstruction, the

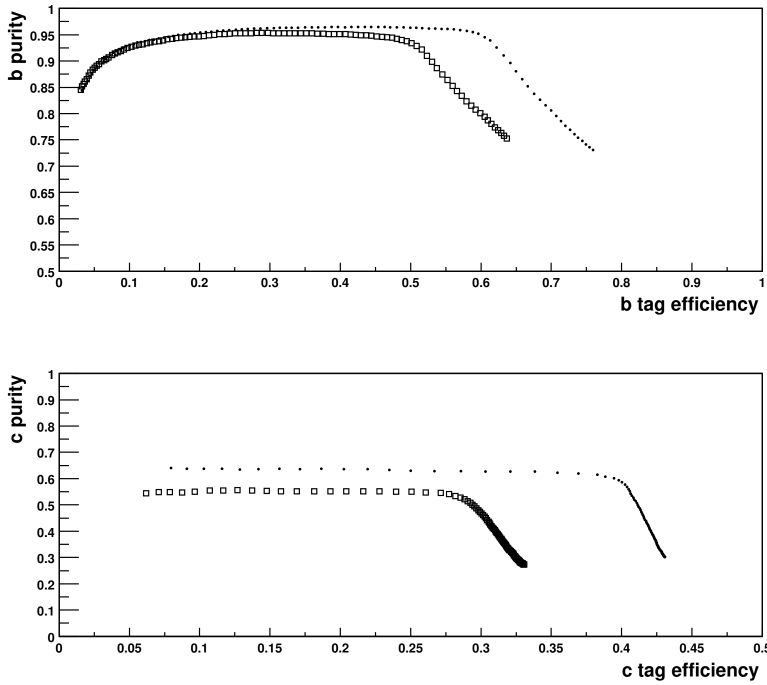

FIGURE 2. Bottom and charm flavor tagging performance for a CCD vertex detector with inner radius of 1.2 cm or 2.4 cm.

importance of these parameters have been studied, yielding consistent results. [8] The charm tagging with the proposed TESLA CCD vertex detector is shown to improve significantly over the past CCD vertex detectors.

While these studies provide important guidance on the design of the vertex detector, ultimately the precision of specific measurements must be understood. One such measurement that has been studied is the Higgs branching ratios. Recently the sensitivity of these measurements to the choice of vertex detector parameters has been studied. [9] In this study, the neural net analysis reduces the sensitivity of the measurement to detector parameters. Processes requiring secondary/tertiary vertex separation should be more sensitive.

The higher energy linear collider will raise further demands on vertex detection. For example, the high energy jets found at a 3 TeV CLIC would lead to some very long decay lengths of several centimeters. It has been proposed that this will demand track counting based on pulse height information, [10] although pixelated information will certainly be important and powerful at CLIC.

The studies presented at this workshop are ongoing, and much remains to be understood regarding the importance of many options in technology and parameters.

Detector R&D

While vertex detection has advanced significantly in the past decade, advances continue, and some of these will certainly be important at the next Linear Collider.

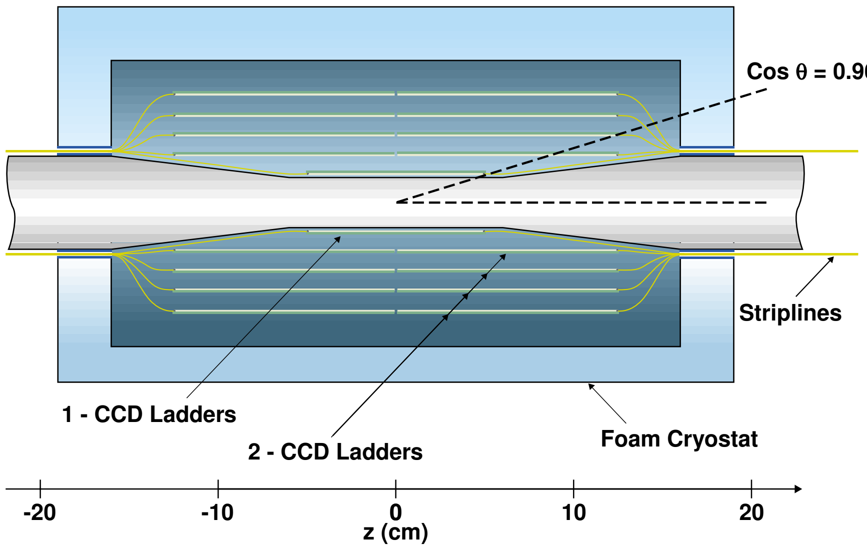

FIGURE 3. The five layer CCD vertex detector proposed by the LCFI Collaboration.

Here we concentrate on those presented at the workshop, recognizing that others not presented here will contribute to our choices. Absence of any work from this summary should not be viewed as a judgment of relevance

Charge Coupled Devices (CCDs)

As described above, CCDs have proven to be the most precise technique to date in vertex detection, and their demonstrated performance at the system level in the existing linear collider (SLC) is an important milestone. Further improvements are being developed for the next Linear Collider. The LCFI (Linear Collider Flavor Identification) Collaboration has launched an R&D program to push all of the parameters of the vertex detector beyond those achieved at SLD. [11] Table 1 lists the goals of the LCFI Collaboration compared to the achievements of SLD. The LCFI Collaboration concept employs a five barrel CCD vertex detector, with 799,000,000 pixels. The three hit coverage extends to $\cos\theta = 0.96$. (see Figure 3) In addition to these performance increases, the LCFI Collaboration plans to develop a new readout architecture for TESLA where the readout register of the traditional design is replaced by a readout chip outside the detector. Since the detector must be readout 20 times during each bunch train of the TESLA beam, the readout register approach will not provide sufficient speed. This parallel column readout is under study and appears feasible. [11]

In Japan, a near-room temperature application of CCDs is under study. [12] (SLD operated at 185K, as is proposed for the next Linear Collider in the US and Europe). Mechanical design studies have been completed, employing a laser

TABLE 1. Vertex Detector Goals of the LCFI Collaboration

	LCFI Coll. goal	SLD VXD3
beampipe thickness	0.07% X_0	0.35% X_0
layer thickness	0.06% X_0	0.4% X_0
hit resolution	3 μm	4 μm
imp. para. resol.	$3.8\ \mu m \oplus \frac{6.6\ \mu m}{\mathrm{p}\ \sin^{\frac{3}{2}}\theta}$	$9\ \mu m \oplus \frac{33\ \mu m}{\mathrm{p}\ \sin^{\frac{3}{2}}\theta}$
3 hit coverage	$cos\theta < 0.96$	$cos\theta < 0.80$
readout speed	25 MHz (outer barrels) 50 MHz (inner barrel)	5 MHz

measurement system with one μm precision. Studies of the radiation hardness of this near-room temperature operation have shown that the system will survive for ten years after the identified charge transfer inefficiency (CTI) improvements. The overall improvement in vertical CTI is better than 60, with improvements coming from increased readout speed (1.3), two-phase CCD operation (2.5), notched CCDs (3 to 4), and "Fat zero" operation (6 to 8).

Active Pixel Detectors: Hybrid and Monolithic

While CCDs have demonstrated outstanding performance at the SLC, the increasing radiation exposure at a higher energy linear collider motivates the consideration, and development, of active pixel detectors (APDs). In order to make the performance of the active pixels competitive with the CCDs, one needs point resolutions of a few μm and detector thickness much less than $1\% X_0$.

A hybrid APD effort in Europe has set goals of 5-7 μm point resolution with less than $0.5\% X_0$ thickness for a new generation of pixel detectors. [13] To achieve this, they are developing a pixel structure with readout only from a subset of the implanted pixels, relying on the capacitive coupling between pixels to achieve the point resolution. Figure 4 illustrates this structure. This collaboration has demonstrated a well understood charge sharing with a prototype test, and are planning a beam test with an improved device.

Another effort is attempting to solve the resolution/thickness problem by developing silicon sensors with three dimensional architecture. [14] In these "3-D" pixel detectors, the n and p electrodes penetrate through the entire substrate. The column electrodes shown in Figure 5 are formed by first etching narrow holes through the wafer using micro-machining techniques. The dummy sensors and readout chips developed to date have been bump-bonded with great success, operate at very low depletion voltages (< 10 V), and are nearly edge free. Plans include a prototype system in the near term.

Yet a third approach to the application of active pixels in the linear collider involves the development of CMOS based monolithic APDs. [15] As with the de-

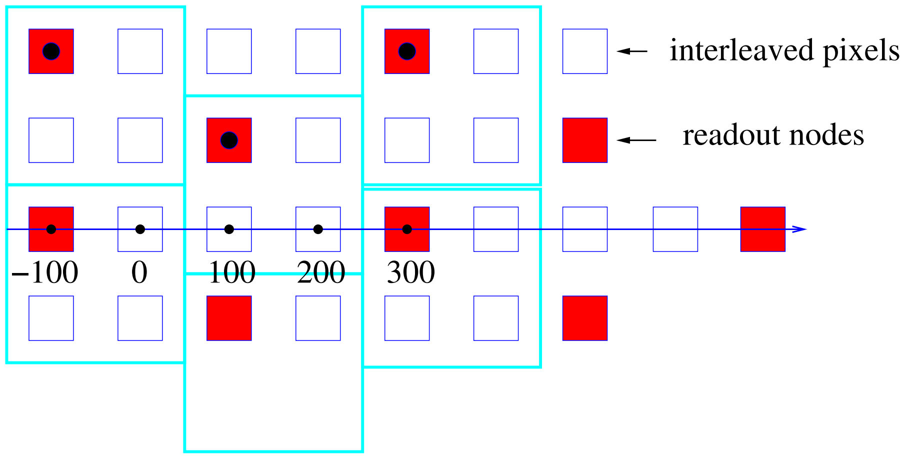

FIGURE 4. Test structure with 100 μm pitch and 200 μm readout. The eventual VLSI footprint is shown by the boxes.

velopment of CCDs for vertex detection, this effort stresses the value of building on the existing commercial infrastructure and technology. Proponents stress the potential for a rad-hard detector, very thin, with high precision, building on industrial capabilities (which could contain the cost). The first prototype consisting of a 64 $\times$ 64 array, has been tested with promising results. As with the other active pixel efforts, a larger detector of about 10 cm^2 is planned for the coming year. One of the major challenges of this approach will be integrating the intrinsically thin detector into the next level of electronics without spoiling the thinness with the necessary large number of innerconnections.

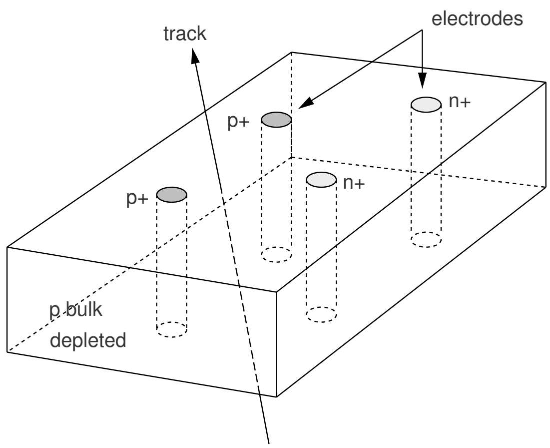

FIGURE 5. "3-D" pixel geometry.

CONCLUSIONS

The physics program of the next Linear Collider promises rich rewards for an optimized vertex detector. With this as a motivation, research and development will continue on all of the efforts referred to in this paper. Further understanding of the impact of design choices is expected in the continuation of the studies currently underway. With several years until the design must be fixed, significant improvements in the technology is possible, if we use this period wisely. Whether the proven technology of CCDs with improvements will be the direction of choice, or the active pixel direction will overcome the CCD lead, the vertex detectors for the next Linear Collider promise to provide an extremely valuable tool for invesigating the processes which will emerge at the next Linear Collider.

ACKNOWLEDGEMENTS

The author is grateful to the organizers of LCWS2000, and the contributors to the vertex detector session for their assistance in the preparation of this summary. This work was supported by the U.S. Department of Energy and the Stanford Linear Accelerator Center.

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