# Performance of the SLD CCD Pixel Vertex Detector and Design of an Upgrade\*

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#### Abstract

We present the performance of the SLD CCD pixel vertex detector (VXD2) after two years of running experience in the SLC  $e^+e^-$  beam environment and the design of a significantly improved upgrade (VXD3) to be installed in late 1995. The existing VXD2 has performed very reliably. A spatial resolution of  $\sim 5 \ \mu m$  in both the  $R\phi$  and Z coordinates has been achieved. Impact parameter resolutions of 11  $\mu m$  in the  $R\phi$  view and 38  $\mu m$  in the RZ view for high momentum tracks are observed from the data. The upgraded design has full three layer solid angle coverage to  $|cos\theta| = 0.85$ , using CCDs at a much larger size of  $8.0 \times 1.6$  cm. Optimized geometry and reduced material will improve the impact parameter resolution by a factor of two compared with VXD2. This upgrade will greatly enhance the heavy flavor physics potential of SLD, allowing a unique exploration of the  $B_s$  mixing time evolution measurement in an interesting  $x_s$  region.

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# 1. Introduction

The SLD Vertex Detector (VXD2) has been collecting data at the SLAC Linear Collider (SLC) since April 1992. Over the last two years, the SLD collaboration has demonstrated that a large array of charged coupled devices (CCDs) can effectively function as a charged particle tracking detector in a linear collider environment. The success of VXD2 has motivated the SLD collaboration to design and begin construction of an upgraded CCD based vertex detector (VXD3) which will be installed in late 1995, and will enhance the physics capabilities of the SLD detector.

#### 2. VXD2 Overview

The design, construction, and initial performance of the SLD Vertex Detector has been described elsewhere [1, 2]. VXD2 consists of 480 CCDs installed in a cylindrical geometry around the SLC beam pipe. A CCD contains ~ 400  $\times$  600 pixels, each of size 22  $\times$  22  $\mu$ m. Eight CCDs are wire-bonded to an alumina mother board of thickness 250  $\mu$ m to create a CCD "ladder" with an active area of about  $8.5 \times 92 \text{ mm}^2$ . These ladders are arranged in four coaxial layers around the beam pipe with 13 (17) ladders in the two inner (outer) layers. The ladders are mounted in two half-cylindrical beryllium support structures with spring-loaded fixtures. The active region on each ladder extends to approximately  $\pm 4.6$  cm along the direction of the beam axis. The inner (outer) layer subtends a range of  $|\cos \theta| < .85$  (< .75). The detector covers about 75% of  $4\pi$ .

The CCDs are surrounded by a foam cryostat and are cooled to  $-80^{\circ}$ C by flowing N<sub>2</sub> gas through the detector. Cooling the detector suppresses dark currents and the loss due to radiation damage of CCD charge transfer efficiency. Electronic readout is accomplished by clocking the CCD charge to an output node at 1.85 MHz. All CCDs are read out continuously in parallel.

#### 3. Operational Experience and Performance

Backgrounds in the detector come predominately from X-ray conversions and upstream tracks parallel to the beam pipe axis. The parallel track backgrounds are suppressed by deleting clusters having a large number of hit pixels. Electronic noise is minimal, less than 1 hit/CCD for each event. Although all backgrounds add up to less than .01% occupancy in the detector, the ratio of background to signal hits in the detector is about one hundred to one for multi-hadronic events, so that the high granularity and unambiguous three-dimensional space point provided by the CCDs is essential for efficient pattern recognition.

Immediately after the installation of VXD2, it

was discovered that two of the eighty ladders were inoperable due to faulty micro-connectors which connect the ladder to the local electronics cable. A few other CCDs also experienced electronics failures. Apart from these problems which occurred during installation, VXD2 has had only one other CCD failure during its operations. The CCDs, mechanical support structure, and electronics have proven to be extremely reliable and robust. In total, 95% of the 480 channels are completely functional.

The CCDs in each layer of VXD2 cover about 60% of the  $\phi$  angle around the beam pipe with layer 2 (4) covering the gaps in layer 1 (3), giving an average of 2.3 hits/track (Figure 1). One of the consequences of having a nonfunctional ladder is to create a region in  $\phi$  containing only one active CCD. For these regions, a pattern recognition algorithm has been developed which supplements the usual technique of linking tracks from the Central Drift Chamber (CDC) with > 2 VXD2 clusters.[2] The supplemental algorithm allows CDC tracks to be linked with a single Vertex Detector hit. Tracks found in the CDC are initially constrained to go through the primary vertex, which is determined to an accuracy of 7 microns perpendicular to the beam direction (XY) and 40 microns along the beam direction (Z). The position of these tracks on the CCD surface is interpolated, and a search is made for nearby VXD2 hits. Finally, a track candidate, including the initial CDC track and the single VXD2 hit, is fit. Efficiency for linking CDC tracks to VXD2 hits is about 96% and uniform in  $\phi$ , even in regions where the track has traversed only one CCD (Figure 2).

Tracking spatial resolution is measured using CDC tracks with three hits in VXD2. A fit is made to the track using only the VXD2 hits at the minimum and maximum radii. The residual between the third hit and the fitted track have widths  $\sqrt{3/2}$  times the single CCD total tracking precision, including effects due to alignment errors. The global spatial resolution is measured to be 5  $\mu$ m in XY and 6  $\mu$ m in Z.

The two-track impact parameter has been measured for high momentum tracks using muon pairs from  $Z^0$ decays. The tracks are extrapolated to the point of closest approach to the nominal interaction point and the distance between them is computed. Gaussian fits give single track resolutions of 11  $\mu$ m in XY and 38  $\mu$ m in RZ. Including a term for multiple scattering, the error on the impact parameter can be approximated by

$$egin{array}{rll} \sigma_b(XY)&=&11\oplus rac{70}{p\,\sin^{3/2} heta} \ ext{and}\ \sigma_b(RZ)&=&38\oplus rac{70}{p\,\sin^{3/2} heta}, \end{array}$$

where  $\sigma_b$  is in microns, p is the momentum in GeV/c, and  $\theta$  is the angle with respect to the beam axis.



Figure 1. Cross sections of VXD2 and VXD3 showing beam pipe, beryllium support structure, and ladders.



**Figure 2.** The effect of linking single VXD2 hits with CDC tracks. Data and Monte Carlo efficiencies for correctly associating VXD2 hits with CDC tracks are shown. If only an algorithm for linking multiple VXD2 hits to CDC tracks is used, there are large inefficiencies in the solid angle containing only one active ladder. If the algorithm for linking single VXD2 hits is also implemented, linking efficiency is approximately constant.

## 4. VXD3 Upgrade and Expected Performance

The basic components of VXD2 are CCDs which were commercially available in the mid-1980's having an active area of about 1 cm<sup>2</sup>. This relatively small size placed many limitations on the design of the vertex detector. Any detector containing more than 480 CCDs was considered to be too difficult to construct, with not enough space around the beam pipe to mount the local electronic boards. These design compromises included (a) an average of fewer than three hits in the vertex detector for each track, (b) layers which only cover ~ 60% of the  $\phi$  angle, (c) a maximum  $|\cos \theta|$  of 0.75 for multi-hit tracks, and (d) a small and  $\phi$ -dependent lever arm ratio (the ratio of the distance between the inner and outer vertex detector hits to the distance between the inner vertex detector hit and the interaction point) which results in increased track resolution.

In the last several years manufacturing methods have improved, allowing production of much larger CCDs which are being used to construct an upgraded vertex detector (VXD3) designed to rectify many of the deficiencies of VXD2 and to enhance the physics potential of SLD. A comparison of VXD2 and VXD3 specifications is shown in Table 1. Design goals for VXD3 include:

- (1) At least 3 VXD3 hits from each track allowing independent vertex detector pattern recognition.
- (2) Full  $\phi$  angle coverage in each layer.
- (3) Full 3 hit coverage up to  $|\cos \theta| = 0.85$ .
- (4) A consistent lever arm ratio of  $\sim 1$ .
- (5) Minimal material in each layer to decrease multiple scattering errors when determining the impact parameter.
- (6) A readout time of no more than the 160 ms.

These goals have been achieved by using customdesigned CCDs, each with an active area of  $1.6 \times 8.0$  cm and containing 3.2 million pixels of size  $20 \times 20 \ \mu$ m. A ladder consists of two CCDs wire bonded to a beryllium oxide mother card. Electronic readout is done only at the ends of the CCDs. Ladders are arranged into three coaxial layers using a "shingled" geometry with each ladder overlapping its two neighbors (Figure 1). The three layers are placed at nominal radii of 2.84, 3.81, and 4.83 cm giving an average lever arm ratio of 0.7. Each ladder has an active area extending to  $\pm 7.95$  cm along the Z axis.

In order to minimize multiple scattering, the CCDs are 150  $\mu$ m thick, the mother cards are thinned to 380  $\mu$ m, and electronic traces are minimized. Each complete ladder is less than 0.5% of a radiation length thick.

Each CCD has four electronic output nodes simultaneously clocked at a rate of 10 MHz using a two stage output. Signals are read out from both sides of

Parameter	VXD2	VXD3
# Layers	4	3
# Ladders	60	48
# CCDs	480	96
# Pixels $(10^6)$	110	307
CCD Active Size (cm)	1.3 x 0.9	8.0 x 1.6
Active z Length (cm)	9.2	15.9
$\langle \# \text{Hits}/\text{Track} \rangle$	2.3	3.2
% of $\phi$ Covered/Layer	60	100
2 Hit $\cos \theta_{\rm max}$	0.75	0.90
3 Hit $\cos\theta_{\rm max}$	-	0.85
Readout Rate (MHz)	2	10
Readout Time (msec)	160	< 100
$L/L_R$ (%)/Layer <sup>‡</sup>	1.1	0.5
$\sigma_b(XY) (\mu m)^{\dagger}$	$11 \oplus 70/p$	$9 \oplus 29/p$
$\sigma_b(RZ) \ (\mu m)^{\dagger}$	$38 \oplus 70/p$	$14 \oplus 29/p$

Table 1. Comparison of VXD2 and VXD3 Specifications.  ${}^{\ddagger}L/L_R$  is the fraction of a radiation length.  ${}^{\ddagger}This$  expression is for tracks perpendicular to the beam pipe. p is in GeV/c.

the detector, then shaped and digitized using electronics locally mounted around the beam pipe. Digitized signals are carried by fiber optic cables to Fastbus data aquisition modules for final signal processing.

The impact parameter resolution for VXD3 has been significantly improved over VXD2 by choosing materials with adequate rigidity and long radiation length, and by increasing the lever arm ratio. The resolution is parameterized by

$$egin{array}{rcl} \sigma_b(XY)&=&9\oplusrac{29}{p\sin^{3/2} heta} ext{ and } \ \sigma_b(RZ)&=&14\oplusrac{29}{p\sin^{3/2} heta}. \end{array}$$

Track reconstruction extends to at least  $|\cos \theta| = 0.9$ , the maximum angle that a single tracks subtends multiple CCDs (Figure 3). Pattern recognition is greatly enhanced in VXD3 for tracks having  $|\cos \theta| < 0.85$ . These tracks have at least 3 CCD hits, allowing independent tracking in both the Vertex Detector and the Central Drift Chamber. Monte Carlo Studies indicate that ~99% of all tracks with p > 0.25 GeV/c passing through three CCDs are reconstructed by VXD3 alone. Information from these VXD3 track segments will augment track with small polar angles.

#### 5. Physics with VXD3

The SLD collaboration and SLAC plan to produce more than  $5 \times 10^5 Z^0$  multi-hadronic decays with initial state  $e^-$  polarization  $P_e > 80\%$  in the next few years. Many measurements made by SLD will benefit from the increased solid angle coverage and better impact parameter resolution of VXD3 compared to VXD2. By



Figure 3. Comparison of VXD2 and VXD3 RZ profiles showing beam pipe, beryllium support structure, ladders, and CCDs.

tagging charged tracks from B hadron decays to identify events containing initial b quarks, a measurement of  $\frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{Hadrons})} \text{ will be made with an accuracy}$  $R_b =$ of < 1%. The initial state polarization allows a direct determination of  $A_b$  from the forward-backward asymmetry, using  $\tilde{A}^b_{FB} = \frac{3}{4} P_e A_b$ . The extra solid angle provided by VXD3 is in a region where asymmetries are maximal. Similar methods allow measurement of  $R_c$ and  $A_c$ . Reconstruction of charm final states will benefit from improved track resolution. Finally, a measurement of the rate of  $B_s^0 - \overline{B_s^0}$  mixing could be used as a test of CP violation within the standard model. The  $B_s$ meson is expected to have a high oscillation frequency, and any determination of  $x_s$  will require measuring the time dependence of the  $B_s$  decay. Initial studies indicate that  $B_s$  oscillations should be observable for  $x_s \lesssim 20$ .

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