General Properties of CCD Vertex Detectors
• CCD Principles
• Advantages and disadvantages in Vertex Detectors

Requirements for future Linear Collider

SLD VXD3: Features and Performance
• CCDs, electronics, mechanics, etc.
• Survey, resolution, heavy quark tagging, etc.

Proposed CCD vertex detector for the future Linear Collider
• Features
• Performance
• Radiation Tolerance

Other Developments
CCDs were invented more than 30 years ago:

Their use as particle detectors was first proposed more than 20 years ago:
  C.J.S. Damerell et al., Nucl. Inst. and Meth. 185, 33 (1981)

The most advantageous feature of the CCD for particle detection is the highly segmented pixel structure (20 µm x 20 µm x 20 µm) when charge sharing between pixels is used to optimize position resolution, better than 4 µm resolution has been achieved in a large system (307,000,000 pixels) operating for years.

The most limiting feature is the relatively slow readout speed: eg. about 100 msec is required to read out a large detector (Linear Collider well matched to this speed.
  Note: >1000x faster readout is under development)
Pair creation energy is ≈ 3.7 eV, with mild temperature dependence:
3.8 eV at 90 K, and 3.65 eV at 300 K

80 electron-hole pairs per micron of track-length

A detector of thickness < 300 microns deviates from Landau distribution, but for thickness > 10 microns, the deviation is acceptable

VXD3
20 µm thick
~ 27 e⁻ / ADC count
Charge collection principles

n+ on p-type substrate (usually)

lightly doped epitaxial p layer
heavily doped p+ substrate
top ~ 1 µm of p layer doped by ion implantation (n+)

depletion region (~ 5 µm)
charge drifts directly
charge in undepleted p region diffuses, and reflects from p/p+ edge, eventually collected
CCD Charge Storage/Redout

Charge storage and readout principles

- I gates transfer charge from imaging area
- R gates transfer charge across the readout register
< 100 e⁻ ENC for ≤ 10-30 MHz and higher

Noise spectra (a-c) and CDS Noise equiv. (d-f)

a., d.) surface channel
b., e.) buried channel
c., f.) available state-of-the-art output circuits
Physics of future Linear Collider demands the **best possible** vertex detector performance

- event rates will be limited
- physics signals will be rich in secondary vertices

A decade of experience with CCDs in the linear collider environment of SLD has proven its exceptional performance

**CCD System History**

- **VXD1 (1991)** prototype few ladders
- **VXD2 (1992-1995)** complete detector 120,000,000 pixels 2 barrel (effective)
- **VXD3 (1996-1998)** upgrade 307,000,000 pixels 3 barrels
Physics Opportunities of the Linear Collider

- Premier physics goals of linear collider characterized by heavy-quark decays and small cross sections
  - eg.
    - Higgs branching ratios (eg. $c\bar{c}$ in presence of dominant $b\bar{b}$)
    - $t\bar{t}$ (usually 6 jets, 2 b jets)
    - $t\bar{t}h$ (usually 8 jets, 4 b jets)
    - $AH$ (12 jets with 4 b jets)
    - and other reactions
Requirements of the Linear Collider Vertex Detector

- Highly efficient and pure $b$ and $c$ tagging, including tertiary vertices ($b \rightarrow c$)
- Charge tagging (e.g., $b/b'$ discrimination)
- These goals are achieved by optimized impact parameter performance:
  - point resolution $< 4 \, \mu m$
  - detector thickness $< 0.2\% \, X_0$
  - inner radius $< 2 \, cm$
  - good central tracker linking
- Also must take care with timing and radiation hardness
### Linear Collider Environment and CCDs are well matched

- **very small beam spots**
  - well defined primary vertex

- **small diameter beam pipe**
  - precision vertexing and manageable detector area

- **low mass detector**
  - reduced multiple scattering

- **long interval between beam crossings**
  - permits readout in ~10-20 beam crossings

- **highly segmented pixel structure**
  - absorbs high background rate of LC
SLD has demonstrated the power of a **PIXEL** detector in the LC environment

- 307,000,000 pixels
- 3.8 µm point resolution
- Excellent impact parameter resolution
  - $\sigma_{r\phi} (\mu m) = 7.8 \oplus 33/p \sin^{3/2}\theta$
  - $\sigma_{rz} (\mu m) = 9.7 \oplus 33/p \sin^{3/2}\theta$
- Pure and efficient flavor tagging at the Z-pole
  - $\sim 60\%$ b eff with $98\%$ purity
  - $> 20\%$ c eff with $\sim 60\%$ purity
- Decay vertex charge measurement ($Q = -1, 0, 1$)
CCD Vertex Detectors

- 307,000,000 pixels
- 3.8 µm point resolution
- Excellent b/c tagging

VXD3 at SLD

SLD Collab., NIM A400, 287-343 (1997)

J. Brau, Snowmass, July 11, 2001
CCD Vertex Detectors

~ few x 10^{-5} hits per pixel at SLC

~ few% are signal

VXD3 Hit Experience
96 CCDs, n-buried channel
thinned to 180 μm
80x16 mm² active area
307,000,000 pixels (20 microns)³
5 MHz full-frame readout
2 phase R clocking & 3 phase I clocking
4 readout nodes/CCD

Each CCD:
800 (H) x 4000 (V) = 3,200,000
20 μm square elements

800,000 pixels read from each
of four output nodes
### CCD Parameters

<table>
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<td>Image section (10 V clocks at 200 kHz)</td>
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<td>Image area clock type</td>
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<td>Readout register</td>
<td>Each output amplifier</td>
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<tr>
<td>clock type</td>
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<td>No. of pre-scan elements</td>
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<td>No. of amplifiers</td>
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<td>Gate protection</td>
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<tr>
<td>on all gates</td>
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</tbody>
</table>

| Format          | 4 quadrant full frame |
| No. pixels      | 800 Hor x 4000 Vert  |
| Pixel size      | 20 x 20 µm²           |
| Sensitive Area  | 16 mm x 80 mm         |
| Overall chip size | ≤ 16.6 mm x 82.8 mm  |
| Inactive edge spacing | < 300 µm              |
| Thickness       | 180 ± 20 µm           |
| Passivation     | 2 µm polyimide        |
| Image area clock type | 3-phase              |
| Readout register clock type | 2-phase             |
| No. of pre-scan elements | 6                    |
| No. of amplifiers | 4                    |
| Gate protection | on all gates          |
CCDs mounted on kapton flex circuits, stiffened by beryllium

1/2 oz. copper traces
1/2 mil polyimide coverlayer
8 mil diameter round fiducials (48)
on south end of outer flex circuit
soft bondable gold deposited on bond
pads and fiducials
Beryllium connected to CCD ground

Total thickness: 0.4% $X_0$ at normal incidence
0.11% Be, 0.16% CCD, 0.05% kapton, 0.09% metal traces

CCDs attached to the ladder with adhesive pads
and wire-bonded from each end to gold-plated pads
Significant compactification (from VXD2)
16 A/D boards close to CCDs
   24 channels / board
       gain of 100 amplifier
       8 bit flash ADC
microcontroller for:
   XILINX codes
   clock waveforms
   DC offsets
   CCD enable/disable
High speed optical links (1.2 GHz, 2 per board) to FASTBUS VDA
Cluster processing on-line (better than thousand-fold reduction)
VXD3 Electronics

CCD Vertex Detectors

Fastbus System

Inside Detector

Cryostat

J. Brau, Snowmass, July 11, 2001
Fig. 3. The VXD3 readout electronics.
307 Mpix x 5 bytes/pixel (1 pulse height + 4 address) = 1.5 Gbytes
System readout capacity ~ 100 kbytes

Clusters
- single pixel threshold = 4 ADC counts 108 e
- (min-I 1200 e)
- cluster edge finder (after 2 x 2 kernel)
- cluster threshold ~ 270 e
- cluster: 8 pixels (R) x 6 pixels (I)
- 99.9% of charge
Cooling
190K operating temperature (suppresses dark current and CTE losses)
Liquid nitrogen boil-off through fine holes in beryllium beampipe jacket
Foam cryostat
< 20 Watts overall within cryostat
**Mechanics**

VXD3 supported by instrument grade beryllium structure

Components match pinned and doweled for stability

Mating surfaces lapped (1 micron precision)

All joints allow for differential thermal contraction

Two modules clamped together & stably mounted on beampipe via

3 point kinematic mount
CCD Vertex Detectors

All ladders, inner and outer barrels, surveyed to few micron precision

**Optical Survey**

*Coordinate Measuring Machine*

OMIS II (Ram Optics)
aperture: 30.4, 15.2, 20.3 cm
resolution: 2-5 microns (xy); 20-30 microns (z)

**Ladder Survey**

4 views measured (ref: 6 tooling balls)
96 fiducials on CCD surface
42 fiducials on flex strip
26 points on each side of CCD
physical corners of Si wafer
rate: 6 hours per ladder

Estimated accuracy: approx 20 microns

**Barrel Survey**

3 layers measured (ref: 32 tooling balls)
measurements through holey grill
visible outside surface of each ladder
physical corner of top CCD
used symmetry to reduce programming
rate: 5 days per barrel
Survey Results

Ladder Survey Data – Top View

Ladder Survey Data – Side View

CCD Vertex Detectors

Barrel Survey – End View

Barrel Survey – Side View
CCD shape

CCD Vertex Detectors

![Diagram of CCD shape](image)
Internal Alignment

CCD Vertex Detectors

- start from optical survey ~ 20 micron precision
- 1. Doublets connects North and South
- 2. Shingles connects CCDs within layer
- 3. Triplets connects 3 layers
- 4. $Z$, $ee$ connects opposite regions (back-to-back)

96 CCDs, 9 parameters each (3 translation, 3 rotation, 3 shape) plus two additional parameters ⇒ total of 856 parameters
Internal Alignment

CCD Vertex Detectors

Weight Matrix $A_{(5026 \times 866)}$
(geometrically determined)

34770 out of
4,352,516 elements are non-zero
($\sim 0.8\%$ occupancy)

\[
\begin{pmatrix}
\delta x_1 \\
\vdots \\
\delta x_{96} \\
\delta y_1 \\
\vdots \\
\delta y_{96} \\
\delta x \\
\delta y
\end{pmatrix} = 
\begin{pmatrix}
\epsilon_1 \\
\vdots \\
\epsilon_{4160} \\
0 \\
\vdots \\
0
\end{pmatrix}
\]
Survey and Alignment

CCD Vertex Detectors

(a) Doublet
\[ \sigma = 3.83 \mu m \]

(c) Triplet
\[ \sigma = 3.76 \mu m \]

(b) Shingle
\[ \sigma = 3.80 \mu m \]

(d) Pairs
\[ \sigma = 4.05 \mu m \]
CCD Vertex Detectors

$\sigma_r = 7.8 \, \mu m$

$\sigma_z = 9.7 \, \mu m$

J. Brau, Snowmass, July 11, 2001
VXD3 Impact Parameter

CCD Vertex Detectors

\[ \sigma_{r\phi} (\mu m) = 7.8 \oplus 33/p \sin^{3/2} \theta \]

\[ \sigma_{rz} (\mu m) = 9.7 \oplus 33/p \sin^{3/2} \theta \]

T. Abe, NIM A447, 90 (2000)

J. Brau, Snowmass, July 11, 2001
• Parametrize tracks as Gaussian tubes in 3D
• Search 3D space for regions of high “tube overlap”

• Since $B \rightarrow D$, multiple vertices
• Find “seed” vertex
• Attach tracks to “seed”, if $T < 1\text{mm}$, $L > 1\text{ mm}$, and $L/D > 0.25$

D. Jackson, NIM A388, 247 (1997)
\[ M = p_T + \sqrt{M_V^2 + p_T^2} \]

D. Jackson, NIM A388, 247 (1997)
VXD3 Purity and Efficiency

b tagging efficiency and purity

includes two layer tracks

\[ \cos \theta = 0.9 (\geq 2 \text{ Hits}) \]
Precision Vertexing, with complete decay reconstruction, leads to discrimination between $B^+$ and $B^-$

Jet Charge

CCD Vertex Detectors

VXD3 at SLD
$$\delta q = d_{BD} \cdot \text{sign}(Q_D - Q_B)$$

Dipole Charge

- Dipole charge separates $B$ from $B$.

- $b \rightarrow c$ (dq positive)
- $\overline{b} \rightarrow \overline{c}$ (dq negative)

(a) Two-vertex dipole
Ghost Track

Due to precision of vertexing, ghost track is better estimate of B direction than thrust axis.
Ghost track method improves dipole charge tag and decay length resolution

(a) Two-vertex dipole

(b) Ghost track dipole
One important lesson from VXD3: (we should have expected)

Build an outstanding detector and physics analysts will push the performance beyond your expectations!

- 307,000,000 pixels
- 3.8 \( \mu \text{m} \) point resolution throughout the entire system
- 7.8 \( \mu \text{m} \) impact parameter resolution at high energy
Recap of CCD Advantages

**High granularity**
- $20 \times 20 \times 20 \, \mu m^3$ pixels (Intrinsically 3-dimensional)
- superb spatial resolution ($< 4 \, mm$ achieved at SLD)

**Thin**
- $0.4\% X_0$ at SLD (0.1% forseen)
- low multiple scattering

**Large detectors**
- $80 \times 16 \, mm^2$ at SLD
- facilitates ease of geometry

Exceptional **system-level** performance demonstrated
- well matched to Linear Collider
Critical Issues in Optimizing Flavor Tag:

⇒ track resolution
  * determined by technology:
    CCDs offer very best resolution

⇒ outer radius of vertex detector
  * constrained by feasible size
    and modestly by outer detectors

⇒ inner radius
  * limited by LC parameters and detector B field
    ⇒ beam backgrounds
    ⇒ B-field needed to constrain the backgrounds

⇒ radiation immunity
  * design shielding to protect CCDs
  * improve CCD tolerance to radiation
Vertex Detector Design for the future Linear Collider

- **Maximum Precision** ($< 4 \mu m$)
- **Minimal Layer Thickness**
  - $(1.2\% X_0 \rightarrow 0.4\% X_0 \rightarrow 0.12\% X_0 \rightarrow 0.06\% X_0)$
  - SLD-VXD2  SLD-VXD3  Linear Collider stretched
- **Minimal Layer 1 Radius**  $(28 \rightarrow 12 \text{ mm} \rightarrow 5\text{mm})$
  - SLD-VXD3  LC  Schumm challenge
- **Polar Angle Coverage**  $(\cos \theta \sim 0.9)$
- **Standalone Track Finding**  *(perfect linking)*
- **Layer 1 Readout Between Bunch Trains**
- **Deadtime-less Readout**
Proposed Design for Future Linear Collider

CCD Vertex Detectors

~ 700,000,000 pixels
standalone tracking
w/ 5 barrels

J. Brau, Snowmass, July 11, 2001
Suggested layout of Vertex Detector for future $e^+ e^-$ Linear Collider
(Updated October 1999)

Scale:
Barrel 1: L = 100mm, R = 12mm

Chris Damerell
Rutherford Appleton Laboratory
October 1999
Impact Parameter Resolution of LC Proposal

CCD Vertex Detectors

\[ \cos \theta = 0 \]

\[ \mu \]

\[ 3 \mu \]

\[ 5 \mu \]

\[ 10 \mu \]

\[ p (\text{GeV}/c) \]

J. Brau, Snowmass, July 11, 2001
Surface Damage from ionizing radiation hard to $> 1$ Mrad (acceptable for LC)

Bulk Damage results in loss of charge-transfer efficiency (CTE)

Ionizing radiation damage suppressed by reducing the operating temperature

Hadronic radiation (neutrons) damage clusters $\rightarrow$ complexes cooling much less effective
VXD3 Experience on Radiation Damage

SLD Experience during VXD3 commissioning,

An undamped beam was run through the detector, causing radiation damage in the innermost barrel. The damage was observed as the detector was operating at an elevated temperature ($\approx 220$ K). Reducing to 190 K ameliorated the damage.

There is a strong temperature dependence to the effect of exposure.
Background estimates for the next Linear Collider have varied from $10^7 \text{n/cm}^2/\text{year}$ to $10^{11} \text{n/cm}^2/\text{year}$

- $2.3 \times 10^9 \text{n/cm}^2/\text{year}$ (Maruyama-Berkeley2000)

Expected tolerance for CCDs in the range of $10^9-10^{10}$

Increase tolerance to neutrons can be achieved through:

- improve understanding of issues and sensitivity
- engineering advances
- flushing techniques
- supplementary channels
- bunch compression & clock signal optimization
- others
Radiation Hardness Tests of CCDs - N. Sinev

This study investigated flushing techniques on spare VXD3 CCD

Flash light to fill traps, then read out

@SLAC \( \sim 2 \times 10^9 \text{n/cm}^2, T_{\text{room}}, \text{Pu(Be)}, \approx 4 \text{ MeV} \)

@SLAC Annealing study \( 100^\circ \text{C} \) for 35 days

@Reactor (I) \( \sim 2 \times 10^9 \text{n/cm}^2, T_{\text{room}}, \text{reactor}^*, \approx 1 \text{ MeV} \)

@Reactor (II) \( \sim 1.2 \times 10^9 \text{n/cm}^2, T\sim190K, \text{reactor}^*, \approx 1 \text{ MeV} \)

Total exposure \( \sim 5.2 \times 10^9 \text{n/cm}^2 \)

Neutron Damage and Amelioration Study

Image of damaged sites

$T = 187K, \text{after dose of } 2 \times 10^9 \text{ n/cm}^2$

Basic concept demonstrated; future work will involve charge injection to keep traps filled.

CCD Vertex Detectors

Image of damaged sites after flushing

$T = 187K, \text{dose } 2 \times 10^9 \text{ n/cm}^2, \text{cleaning charge}$

Other Development Directions

CCD Vertex Detectors

NLC and TESLA - stretched CCDs
• thicknesses reduced to 0.06% $X_0$

JLC - room temperature operation for JLC
• motivated to eliminate cryogenics

TESLA - column parallel readout
and 50 MHz readout
• reduce build-up of background hits during bunch train
1. SLD Collab., “Design and performance of the SLD vertex
detector: a 307 Mpixel tracking system,” Nucl. Inst. And

Inst. and Meth. A447, 90 (2000).


4. C.J.S. Damerell, “Charge-coupled devices as particle tracking
CCDs have been established as a powerful technique for precision vertex detection at SLD
- 307,000,000 pixels
- 3.8 µm hit resolution throughout (years of operation)
- ~ 100 µm decay length resolution (even much better in for specific channels, e.g. Bs → DsX (Ds → φπ))
- many world-leading measurements of heavy quark physics

A CCD Vertex Detector would be a powerful tool at the future Linear Collider

Advances in the technique are planned
- Rad-hardening
- Faster read-out
- Other improvements