CCD Vertex Detectors

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IEEE NPSS Technology Lectures
Snowmass
July 11, 2001

Outline

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

CCD Principles

CCD Vertex Detectors

CCDs were invented more than 30 years ago:

W.S. Boyle, G.E. Smith, Bell Syst. Tech. J. 49, 587 (1970)

Their use a 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)

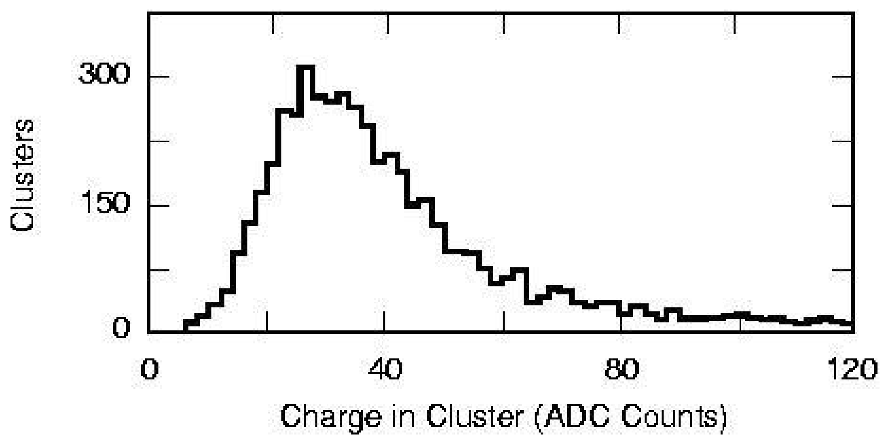
CCD Principles

CCD Vertex Detectors

Pair creation energy is ≈ 3.7 eV, wth 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

CCD Charge Collection

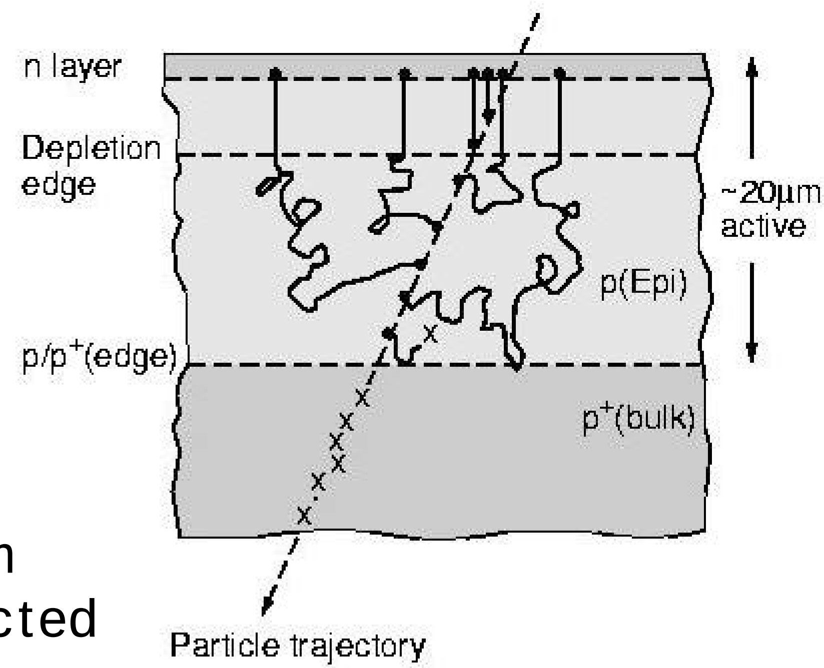
CCD Vertex Detectors

Charge collection principles

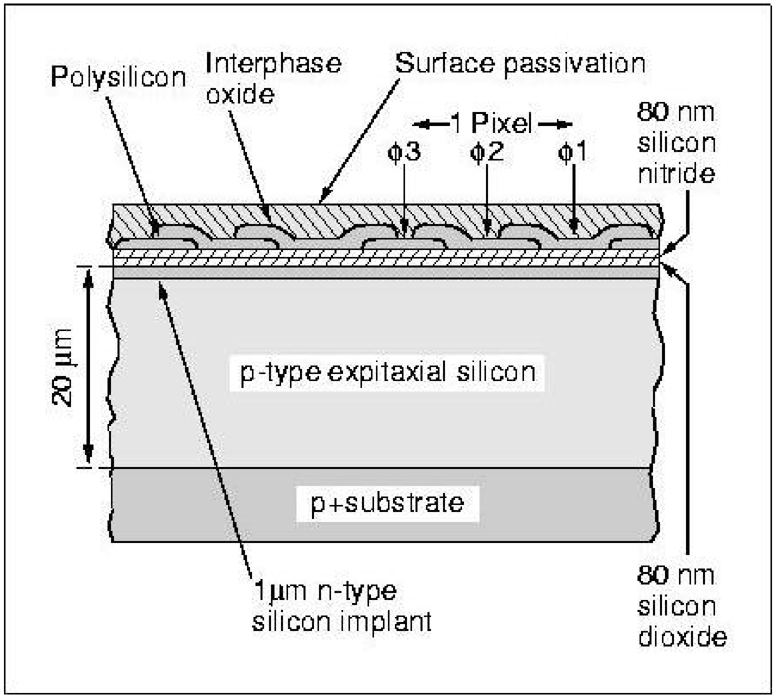
n+ on p-type substrate (usually)

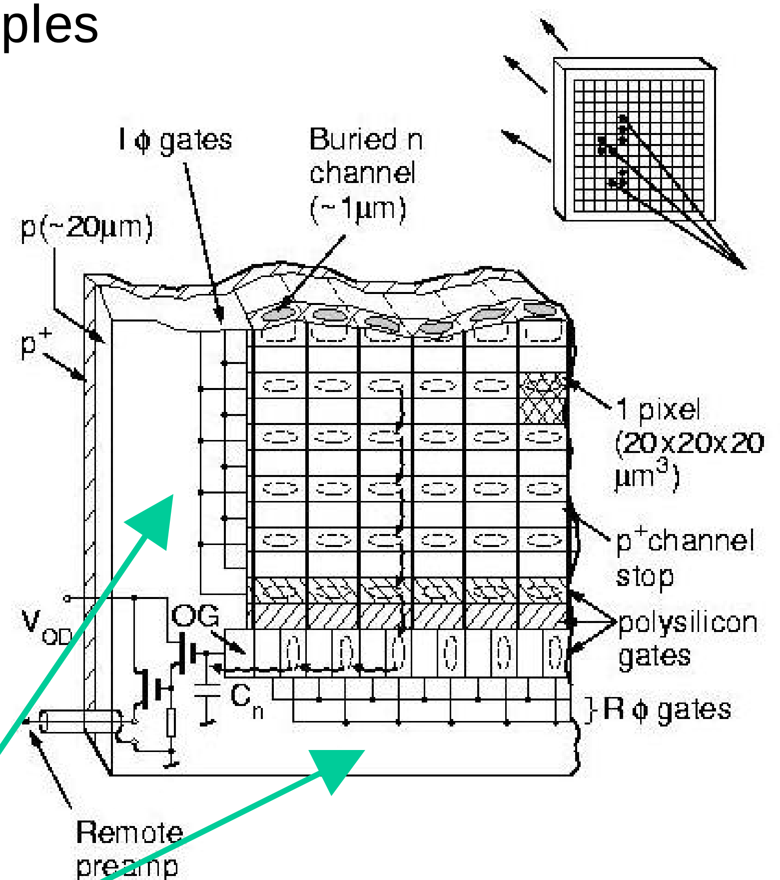
lightly doped epitaxial p layer
heavily doped p^+ substrate
top ~ 1 μm of p layer doped by
ion implantation (n^+)

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



Charge storage and readout principles





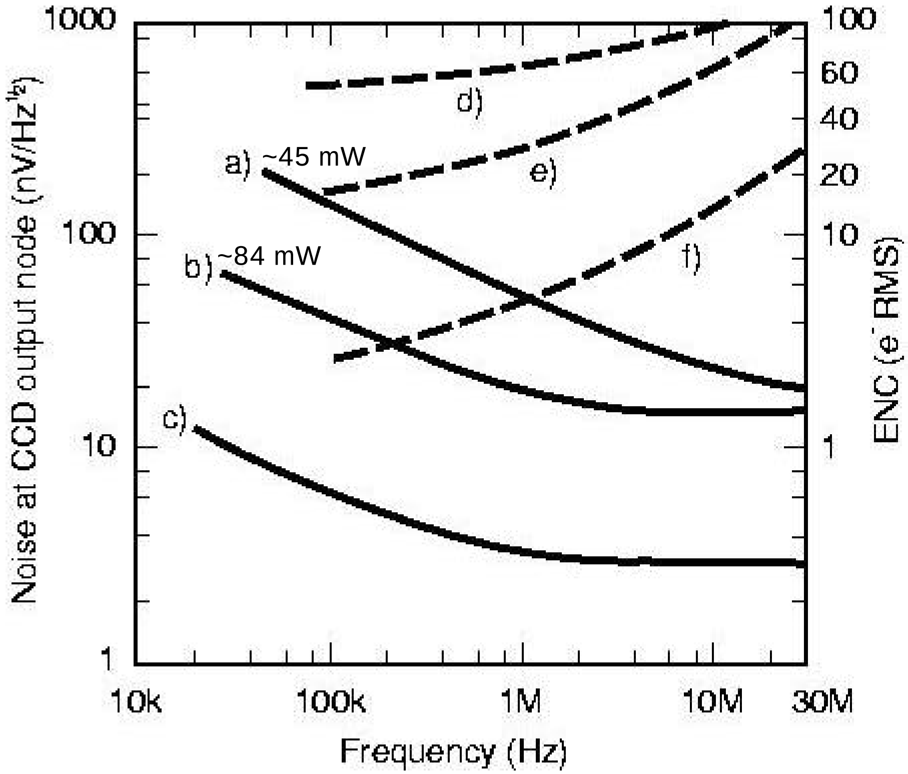
I gates transfer charge from imaging area

R gates transfer charge across the readout register

CCD Noise

CCD Vertex Detectors

< 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

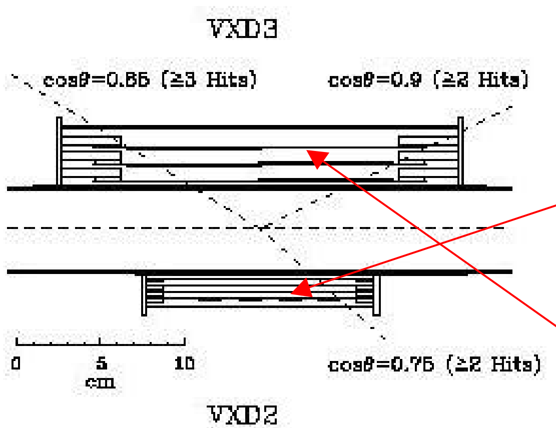
CCD VXD System History

CCD Vertex Detectors

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



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 (eg. $b/\bar{b}$ discrimination)
- These goals are achieved by optimized impact parameter performance:
  - point resolution < 4 μm
  - 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 VXD3

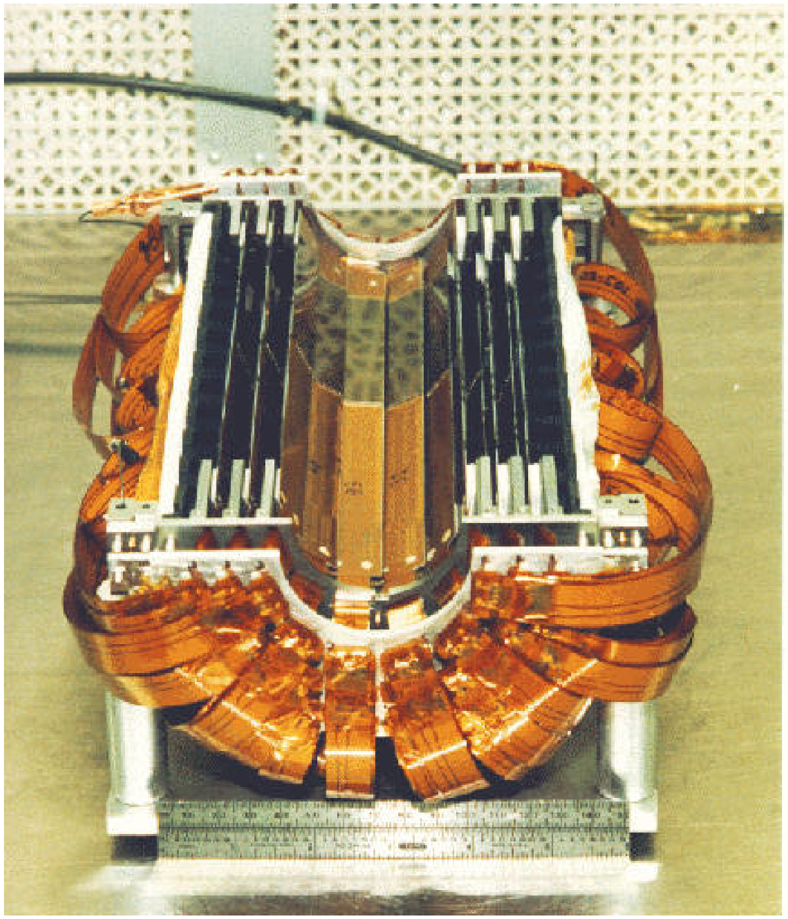
CCD Vertex Detectors

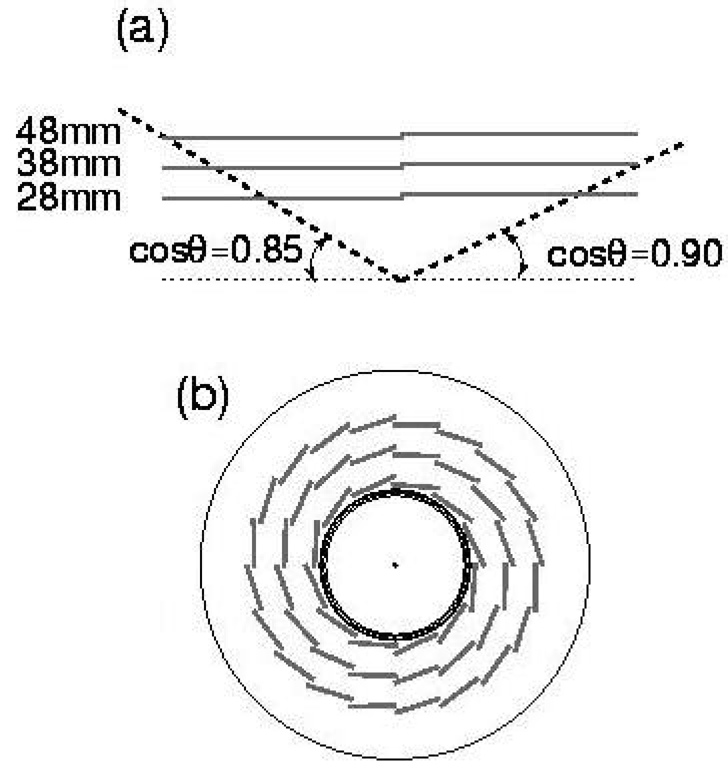
SLD has demonstrated the power of a PIXEL detector in the LC environment

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

VXD3 at SLD

CCD Vertex Detectors



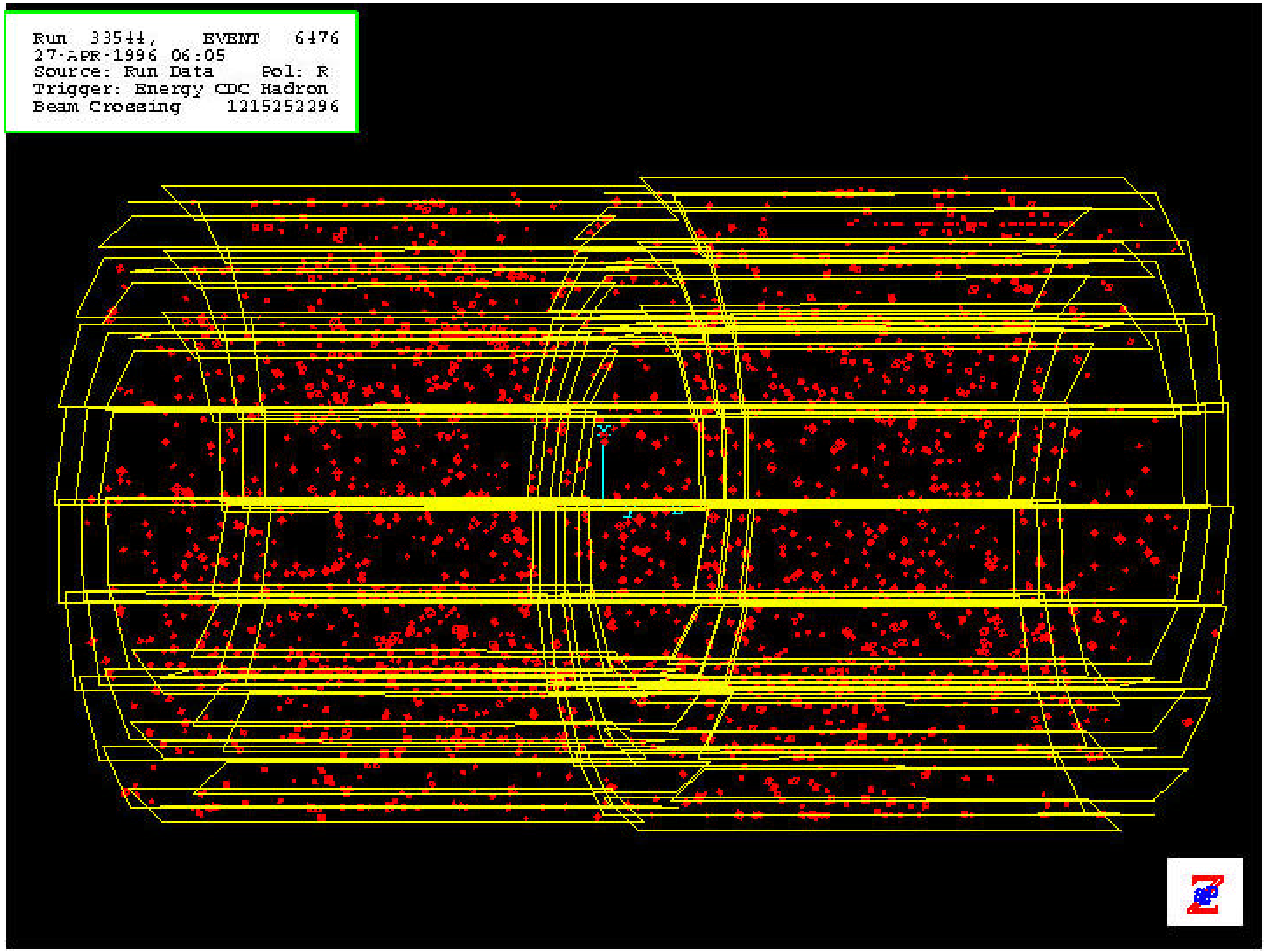


307,000,000 pixels
3.8 μm point resolution
Excellent b/c tagging

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

VXD3 Hit Experience

CCD Vertex Detectors

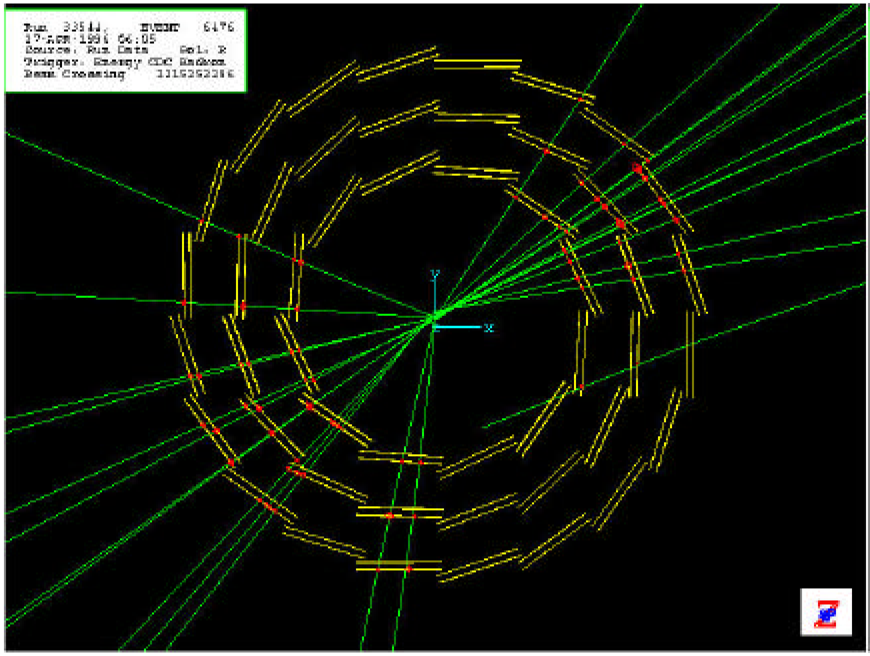


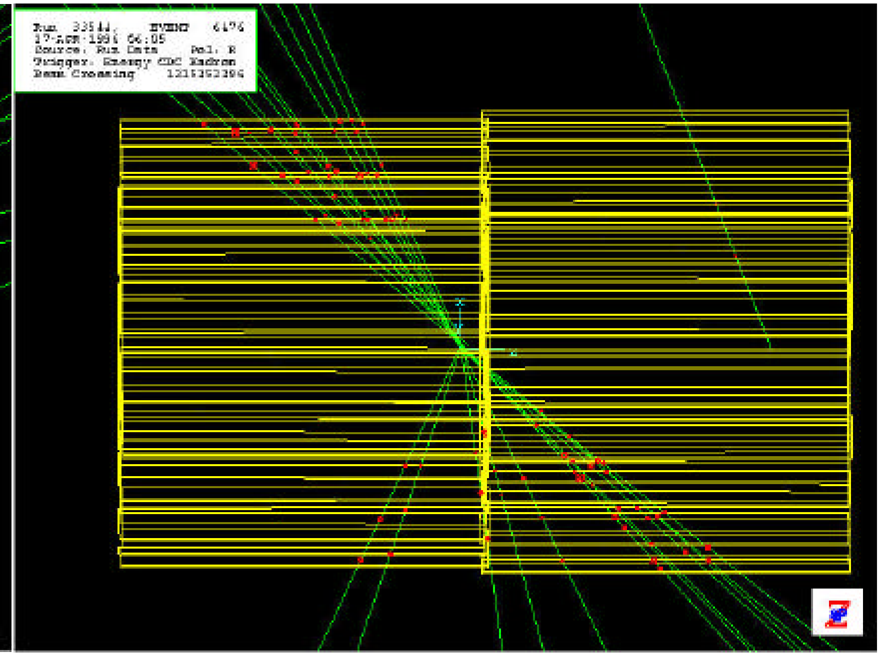
~ few x 10^{-5} hits per pixel at SLC

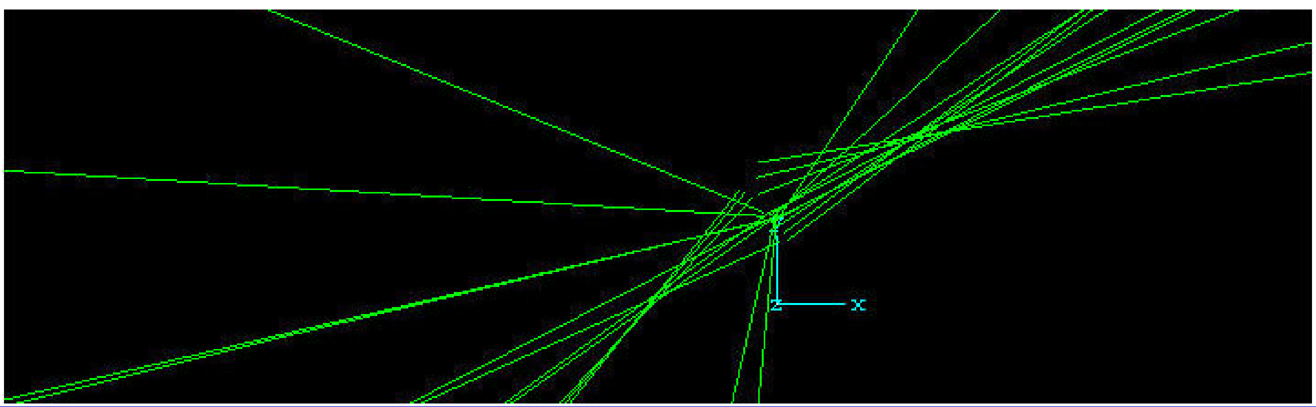
~ few% are signal

VXD3 Event Reconstruction

CCD Vertex Detectors



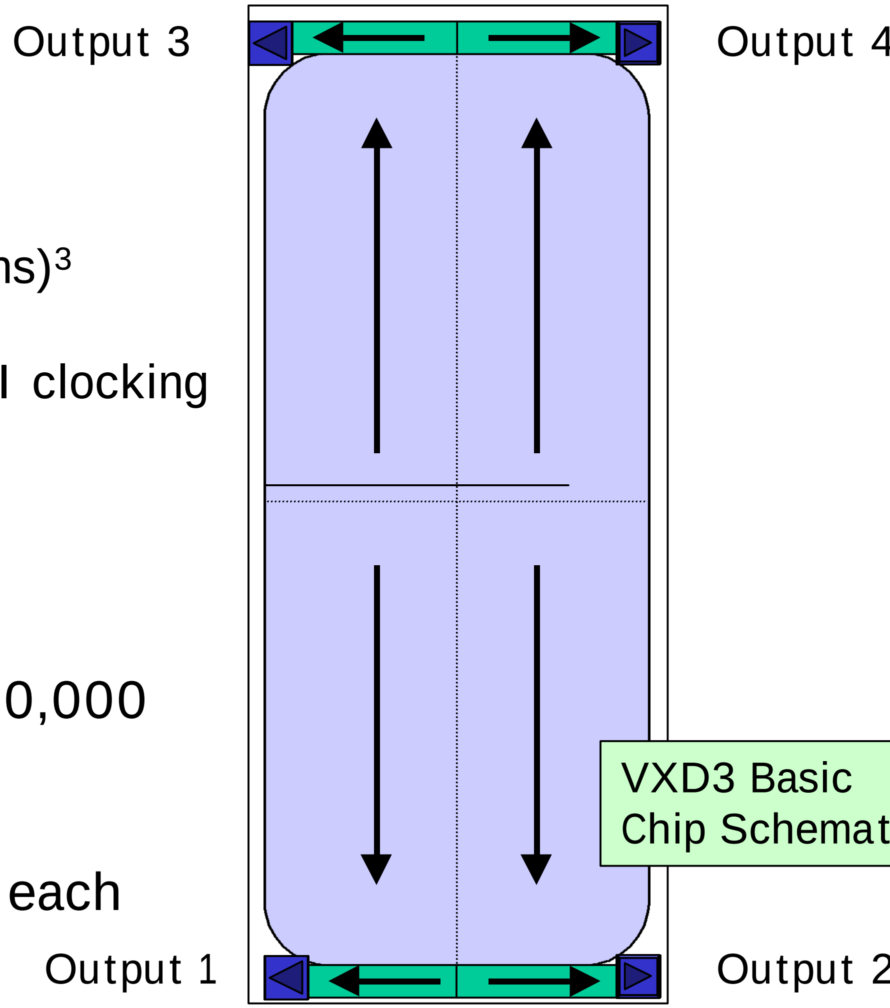




VXD3 CCDs

CCD Vertex Detectors

96 CCDs, n-buried channel
thinned to 180 μm
80x16 mm^2 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



VXD3 Basic Chip Schematic

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

CCD Vertex Detectors

Basic design features	
Substrate resistivity	< 20 mΩ cm
Epitaxial layer reistivity	20 Ω cm
Format	4 quadrant full frame
No. pixels	800 Hor x 4000 Vert
Pixel size	20 x 20 μm^2
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

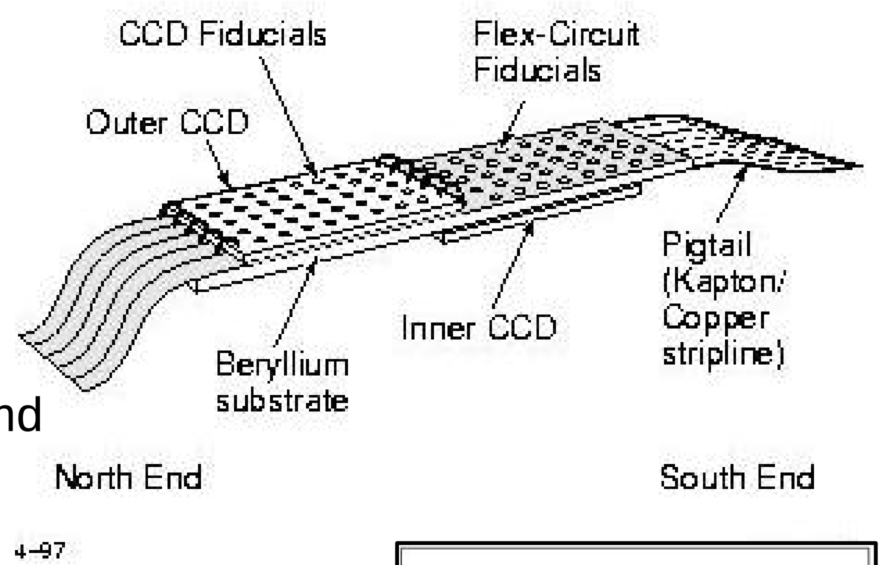
Performance parameters	
Clock capacitances	
Image section to substrate	16 nF
Image section interphase	6 nF
Readout register to substrate	85 pF
Readout register interphase	30 pF
Charge storage capacity	
Pixel (supplmentary channel)	100 x 10^3 e^-
Pixel (total)	350 x 10^3 e^-
Readout register	400 x 10^3 e^-
Vertical transfer rate	> 200 kHz
Horizontal transfer rate	> 10 MHz
Output circuit responsivity	3 µV/ e^-
Output impedence	260 Ω
Power dissipation (on-chip)	
Image section (10 V clocks at 200 kHz)	1.3 W
Readout register (10 V clocks at 10 MHz	25 mW
Each output amplifier	45 mW

VXD3 Ladder Assembly

CCD Vertex Detectors

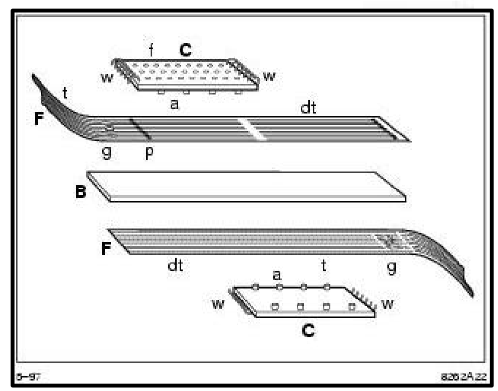
CCDs mounted on kapton flex circuits, stiffened by beryllium

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



VXD3 Electronics

Significant compactification (from VXD2)

16 A/D boards close to CCDs

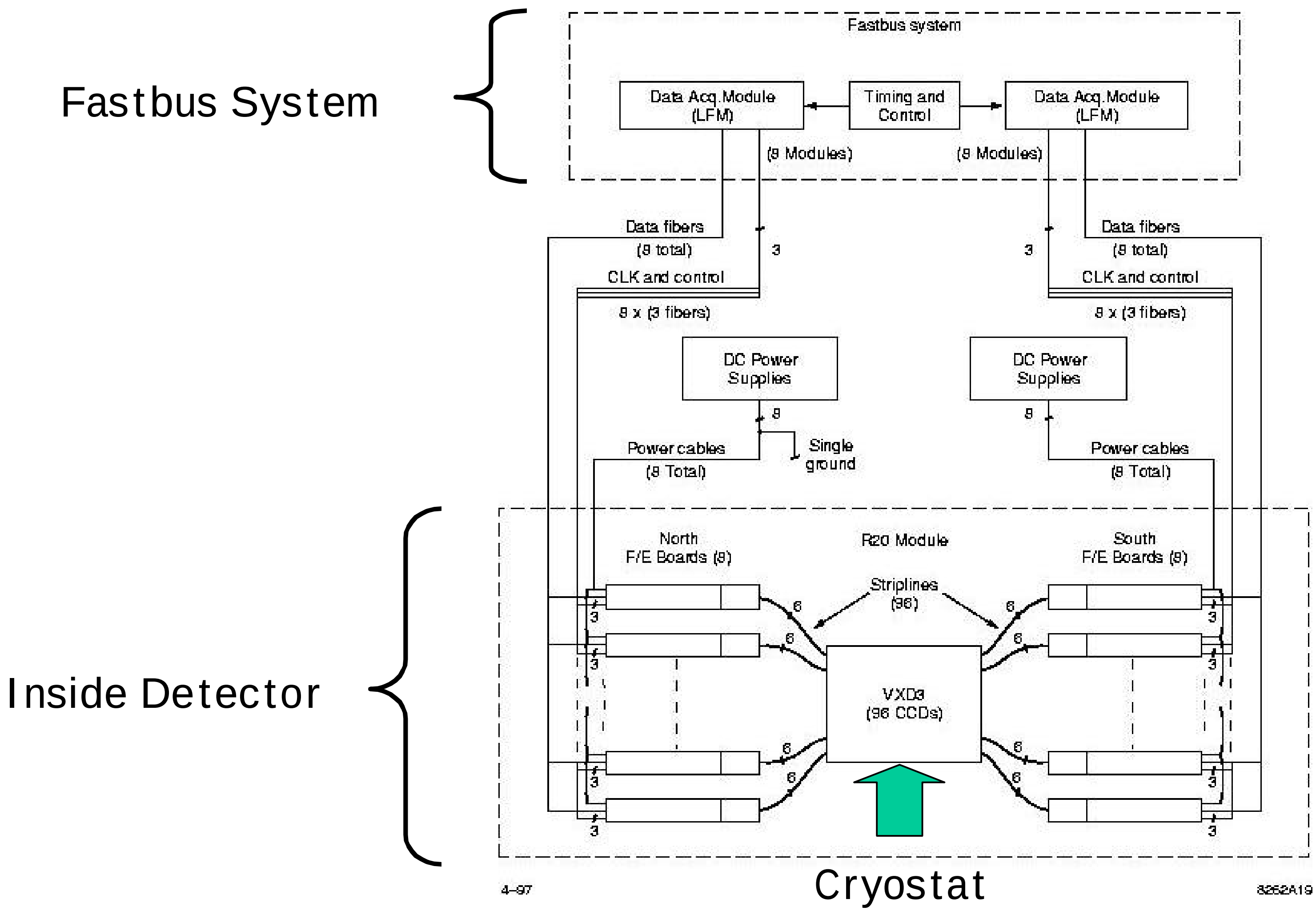
- 24 channels / board
  - gain of 100 amplifier
  - 8 bit flash ADC
- microcontroller for:
  - XILINX codes
  - clock waveforms
  - DC offsets
  - CCD enable/disable

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



VXD3 Electronics

CCD Vertex Detectors

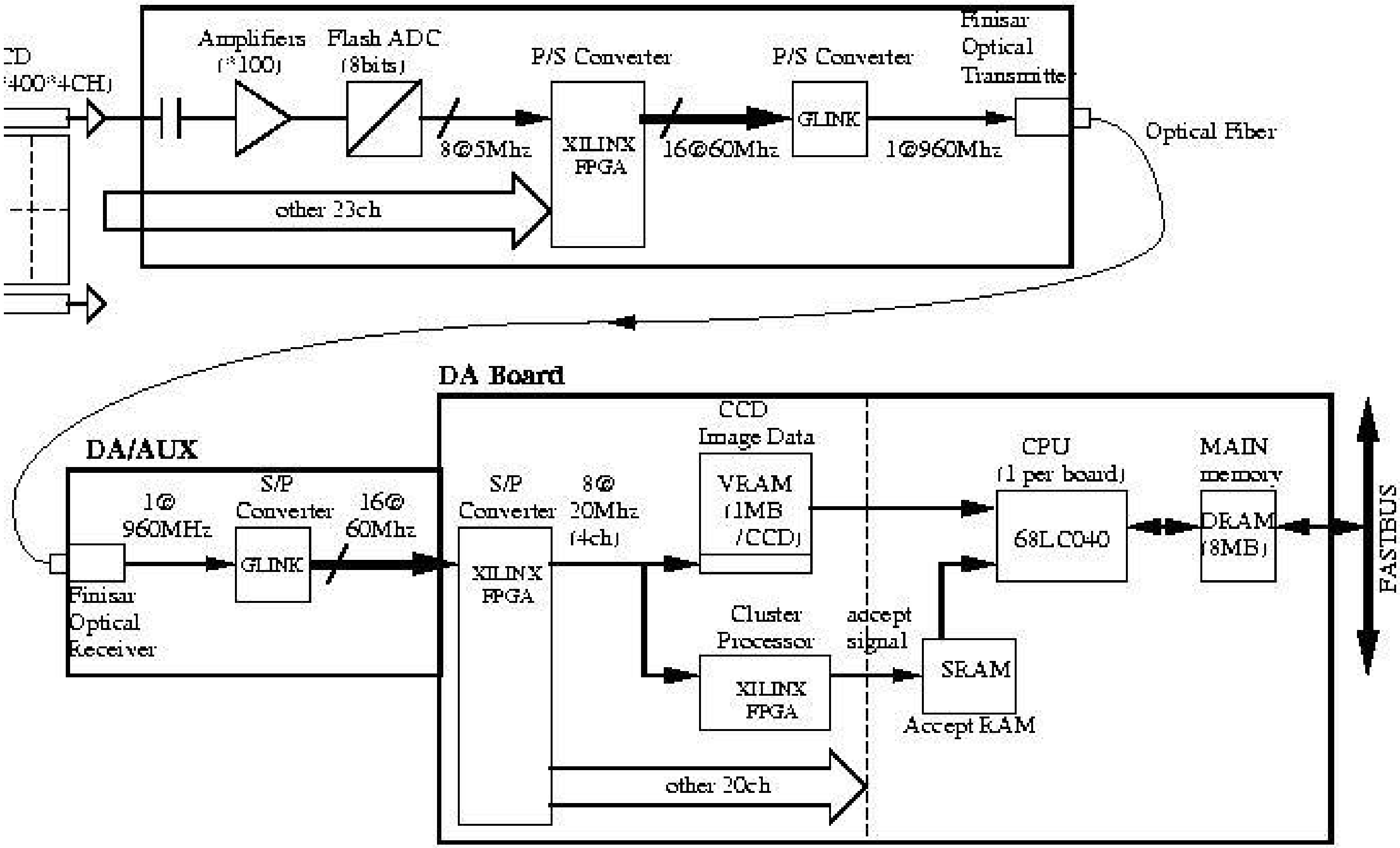


Fig. 3. The VXD3 readout electronics.

Cluster Processing

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

VXD3 Cooling

CCD Vertex Detectors

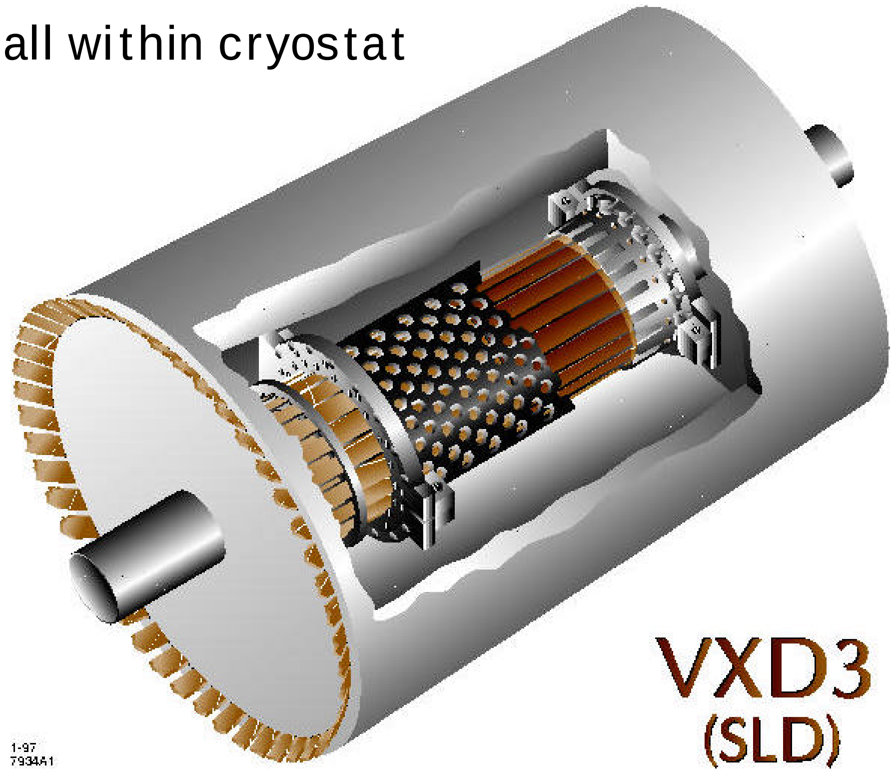
Cooling

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



VXD3 Mechanics

CCD Vertex Detectors

Mechanics

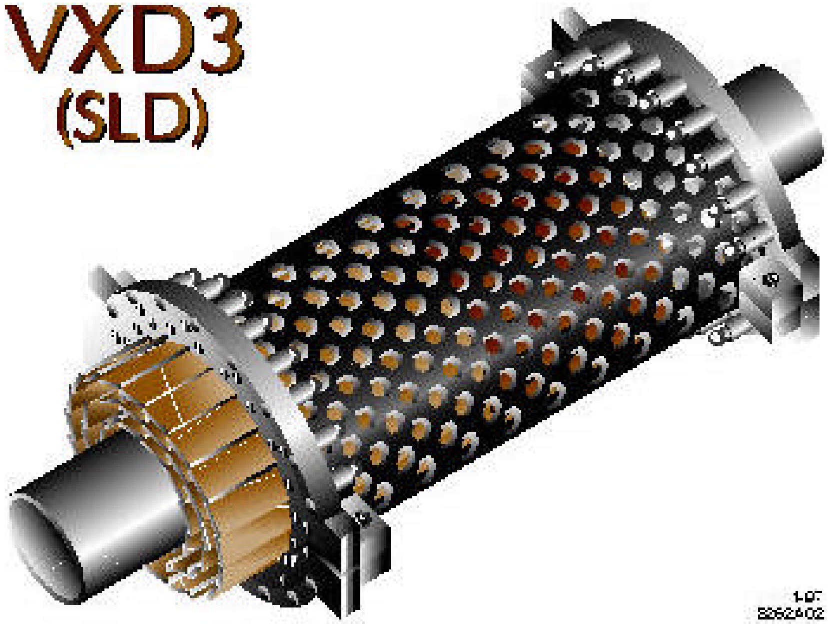
VXD3 supported by instrument grade beryllium structure

Components match pinned and doweled for stability

Mating surfaces lapped (1 micron precision)

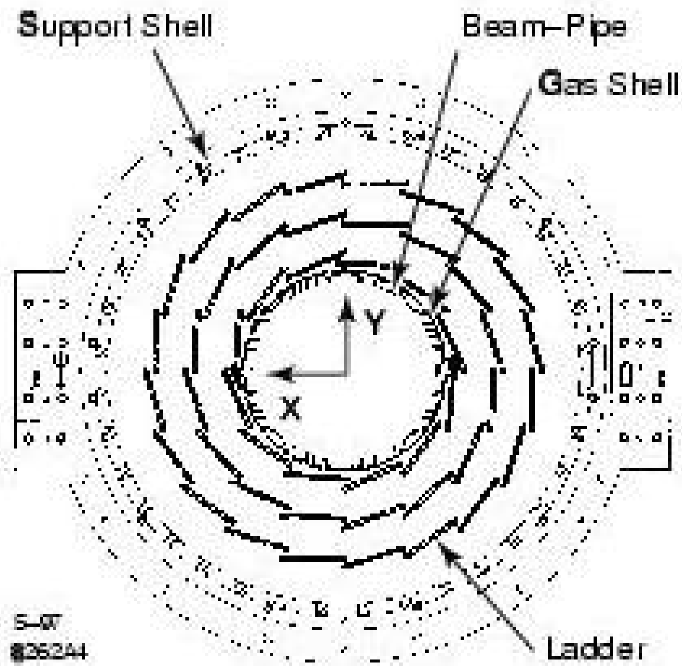
All joints allow for differential thermal contraction

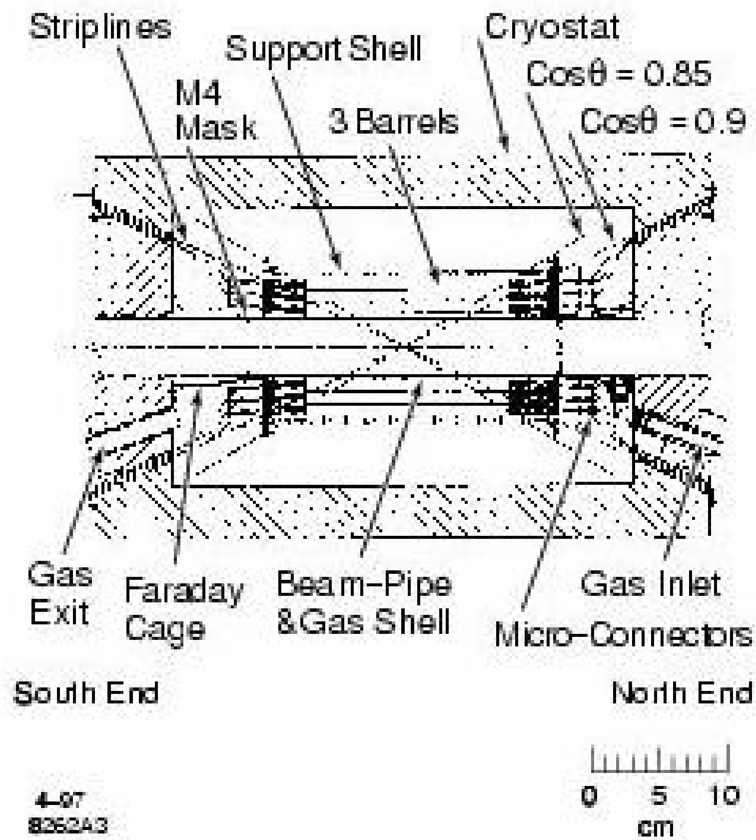
Two modules clamped together & stablely mounted on beampipe via 3 point kinematic mount



VXD3 Mechanics

CCD Vertex Detectors





VXD3 Optical Survey

CCD Vertex Detectors

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

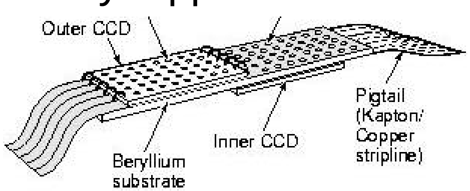
Optical Survey

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

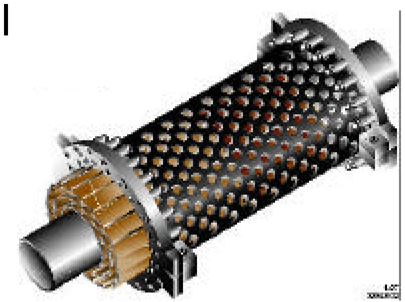
4 views measured (ref: 6 tooling balls)
96 fiducials on CCD surface
42 fiducials on flex strip
26 points on each side of CCD
physical corners of Si wafer
rate: 6 hours per ladder

Estimated accuracy: approx 20 microns



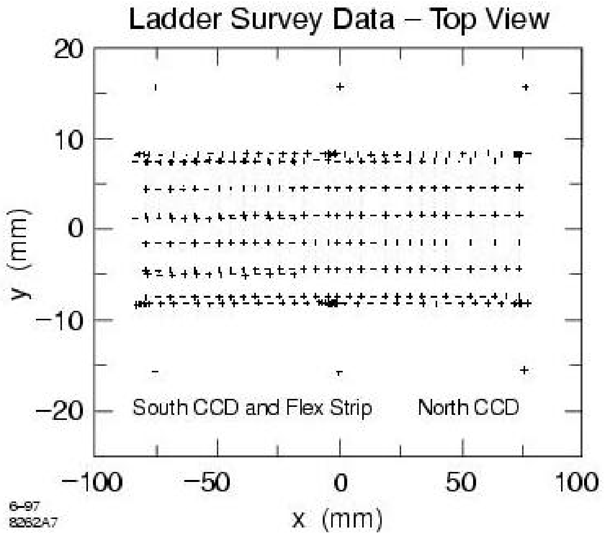
Barrel Survey

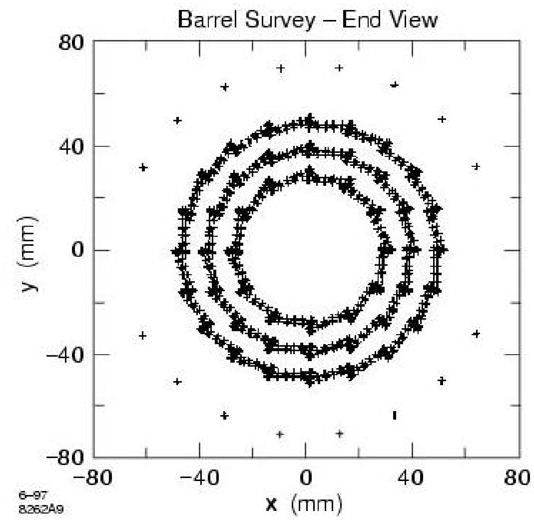
3 layers measured (ref: 32 tooling balls)
measurements through holey grill
visible outside surface of each ladder
physical corner of top CCD
used symmetry to reduce programming
rate: 5 days per barrel

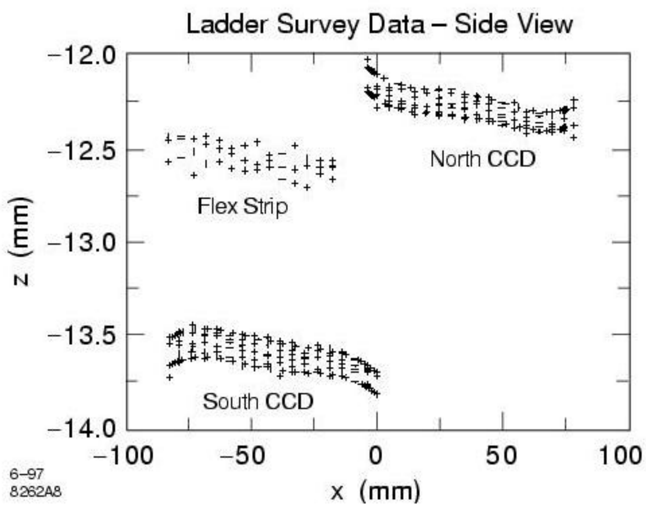


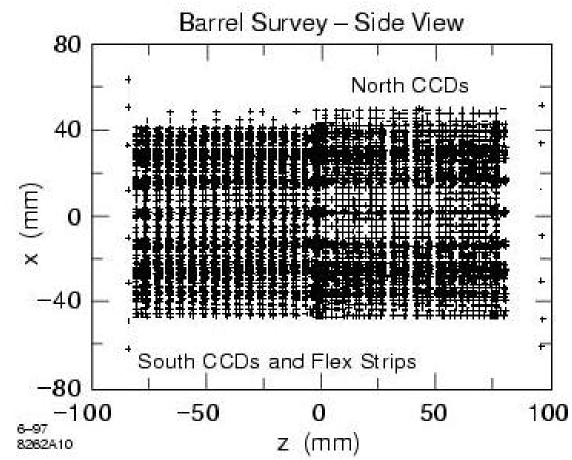
Survey Results

CCD Vertex Detectors



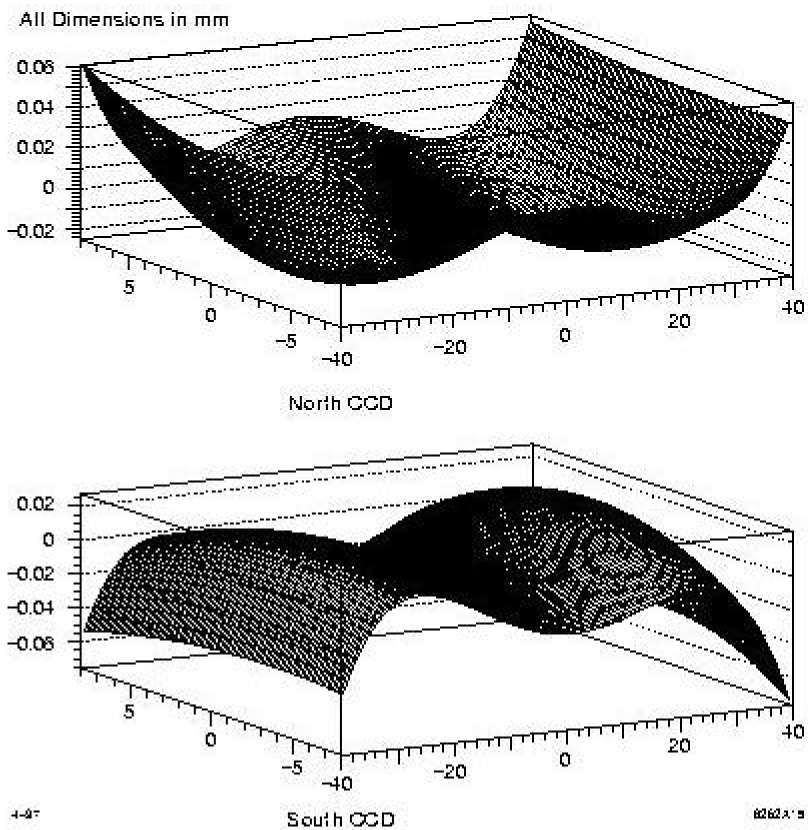






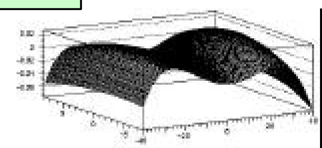
CCD shape

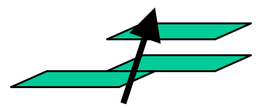
CCD Vertex Detectors

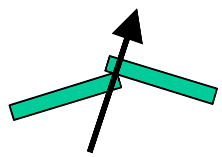


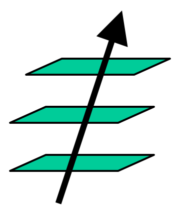
Internal Alignment

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 (back-to-back) connects opposite regions

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

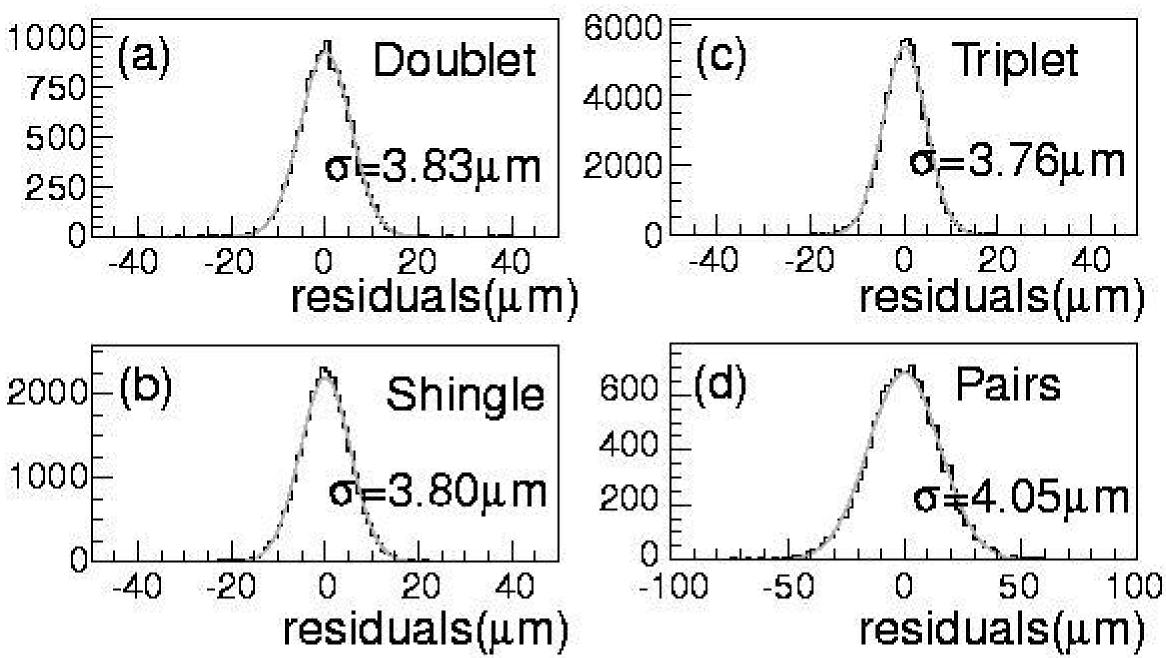
Internal Alignment

CCD Vertex Detectors

$$\begin{pmatrix} \text{Weight Matrix } \mathbf{A} (5026 \times 866) \\ \text{(geometrically determined)} \\ \\ 34770 \text{ out of} \\ 4{,}352{,}516 \text{ elements are non-zero} \\ (\sim 0.5\% \text{ occupancy}) \end{pmatrix} \begin{pmatrix} \delta z_1 \\ \vdots \\ \delta \gamma_{96} \\ \delta g_1 \\ \delta h_1 \\ \vdots \\ \delta l_{96} \\ \delta x \\ \delta y \end{pmatrix} = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ c_{4160} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

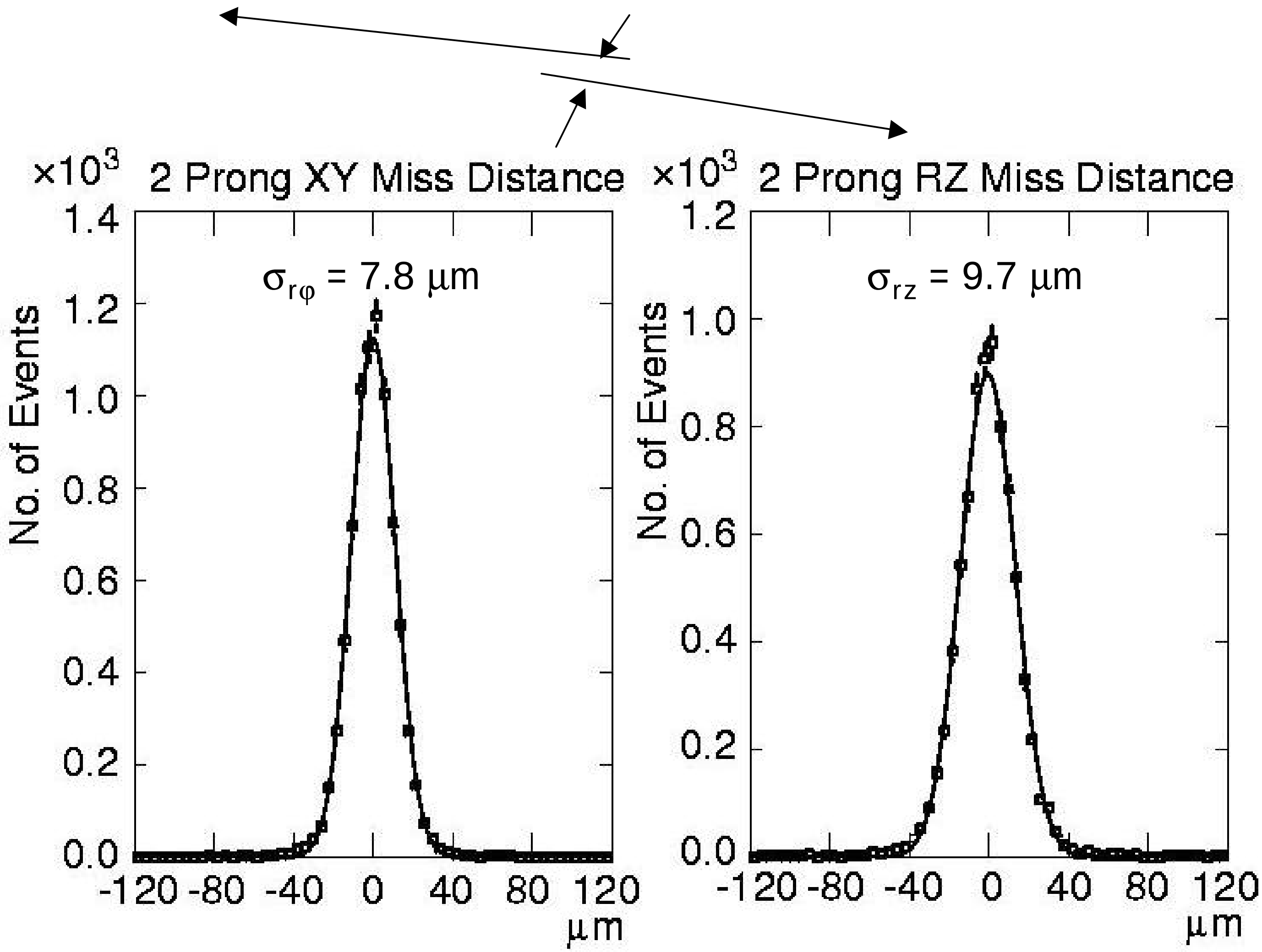
Survey and Alignment

CCD Vertex Detectors



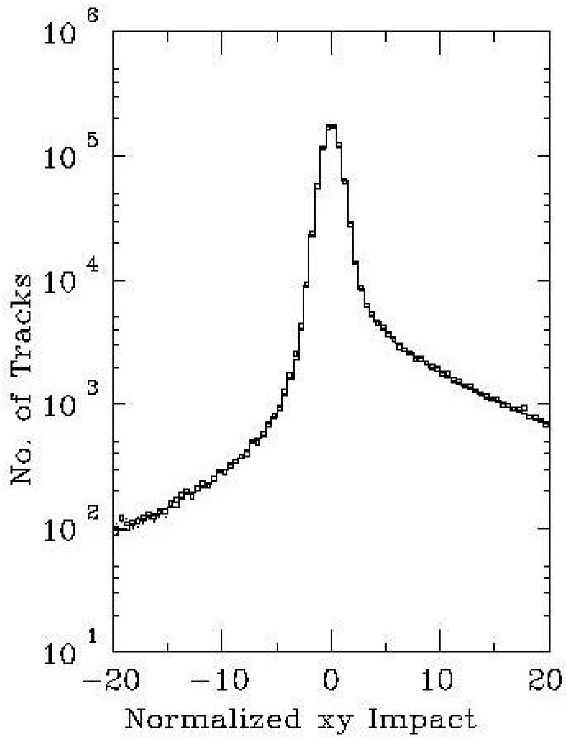
2 Prong Miss Distance

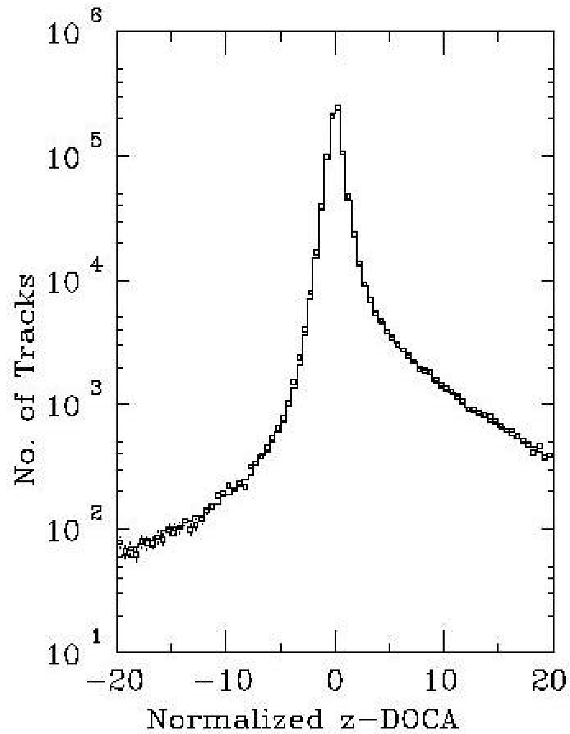
CCD Vertex Detectors



VXD3 Impact Parameter

CCD Vertex Detectors





$\sigma_{r\varphi}$ (μm)= 7.8 $\oplus$ 33/p $\sin^{3/2}\theta$

σ_{rz} (μm)= 9.7 $\oplus$ 33/p $\sin^{3/2}\theta$

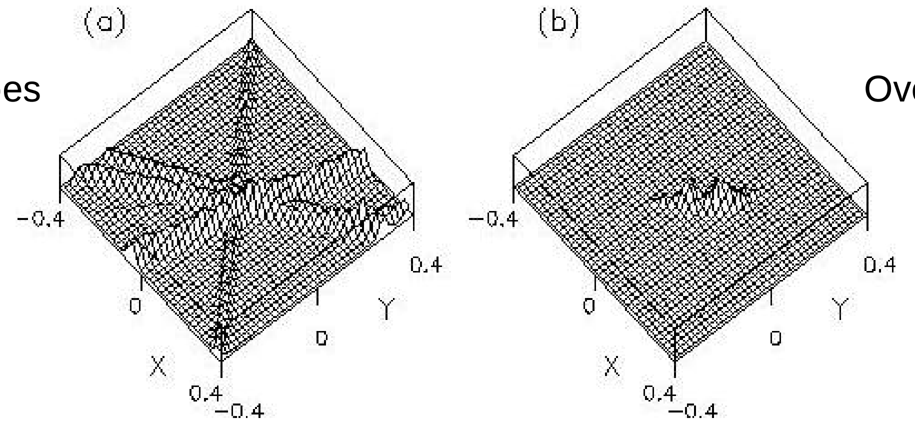
T. Abe, NIM A447, 90 (2000)

Topological Vertexing

CCD Vertex Detectors

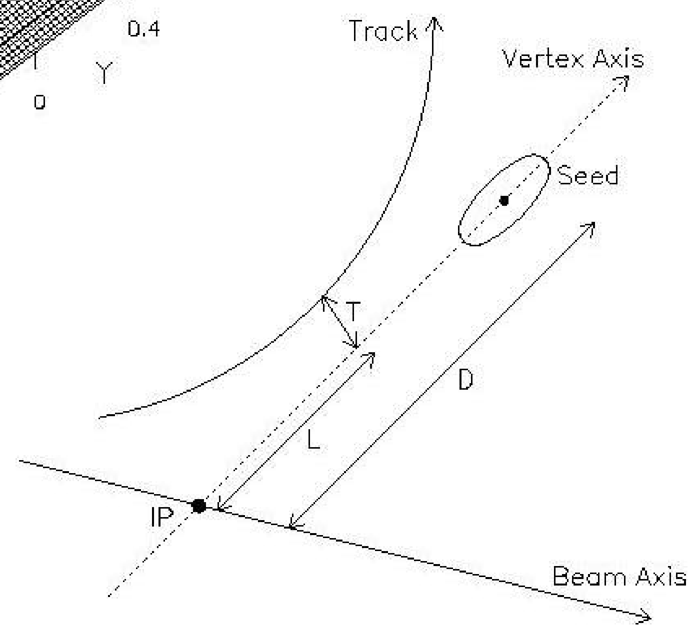
- Parametrize tracks as Gaussian tubes in 3D
- Search 3D space for regions of high “tube overlap”

Tubes



Overlap

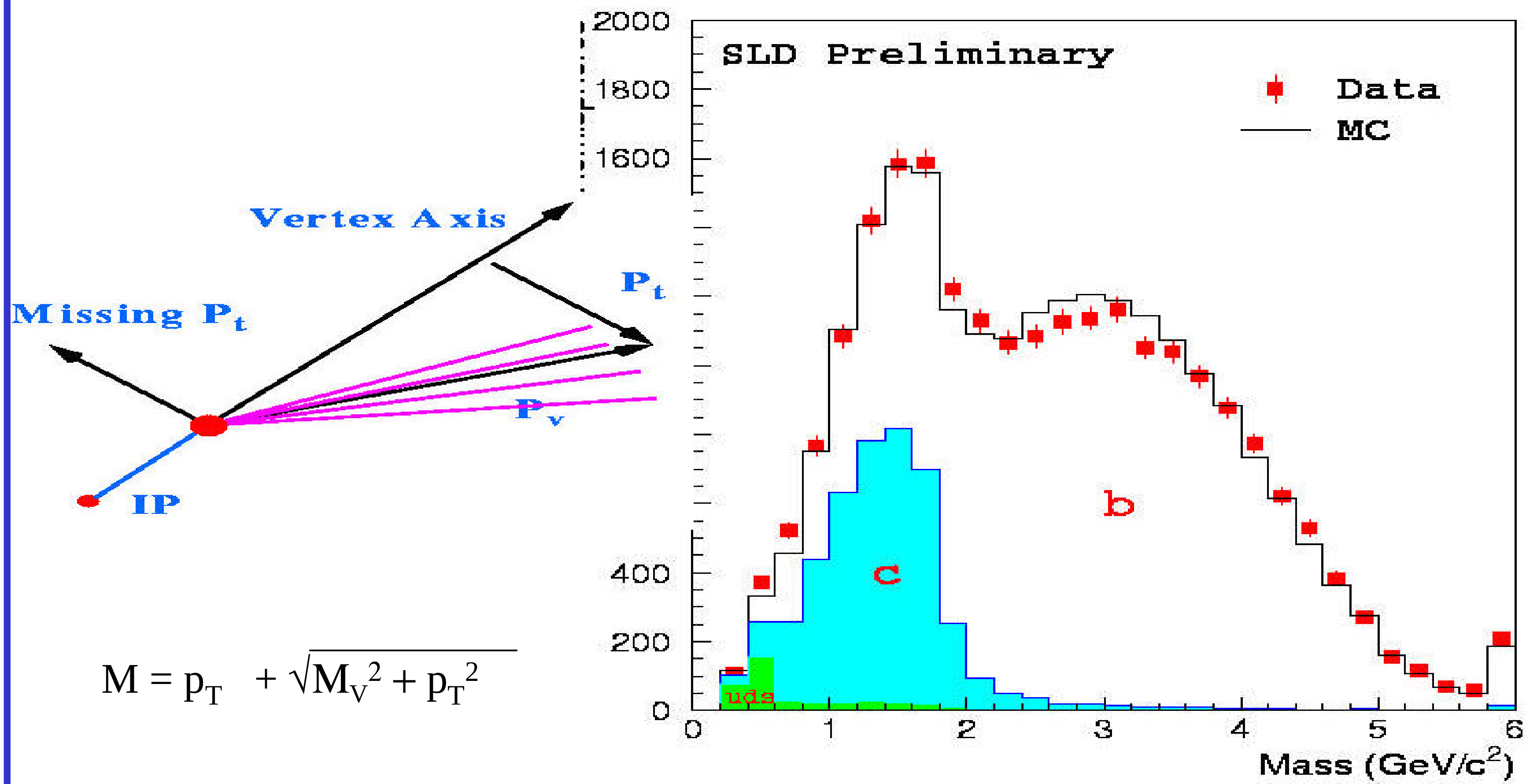
- Since B→D, multiple vertices
- Find “seed” vertex
- Attach tracks to “seed”,
  if T < 1mm, L > 1 mm,
  and L/D > 0.25



D. Jackson, NIM A388, 247 (1997)

Pt Corrected Mass

CCD Vertex Detectors



$$M = p_T + \sqrt{M_V^2 + p_T^2}$$

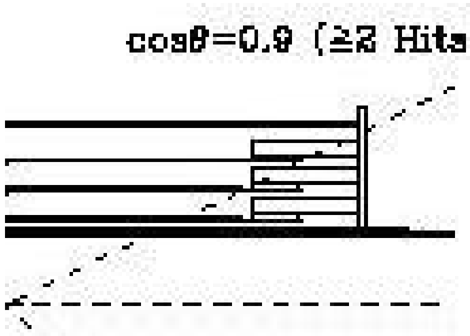
D. Jackson, NIM A388, 247 (1997)

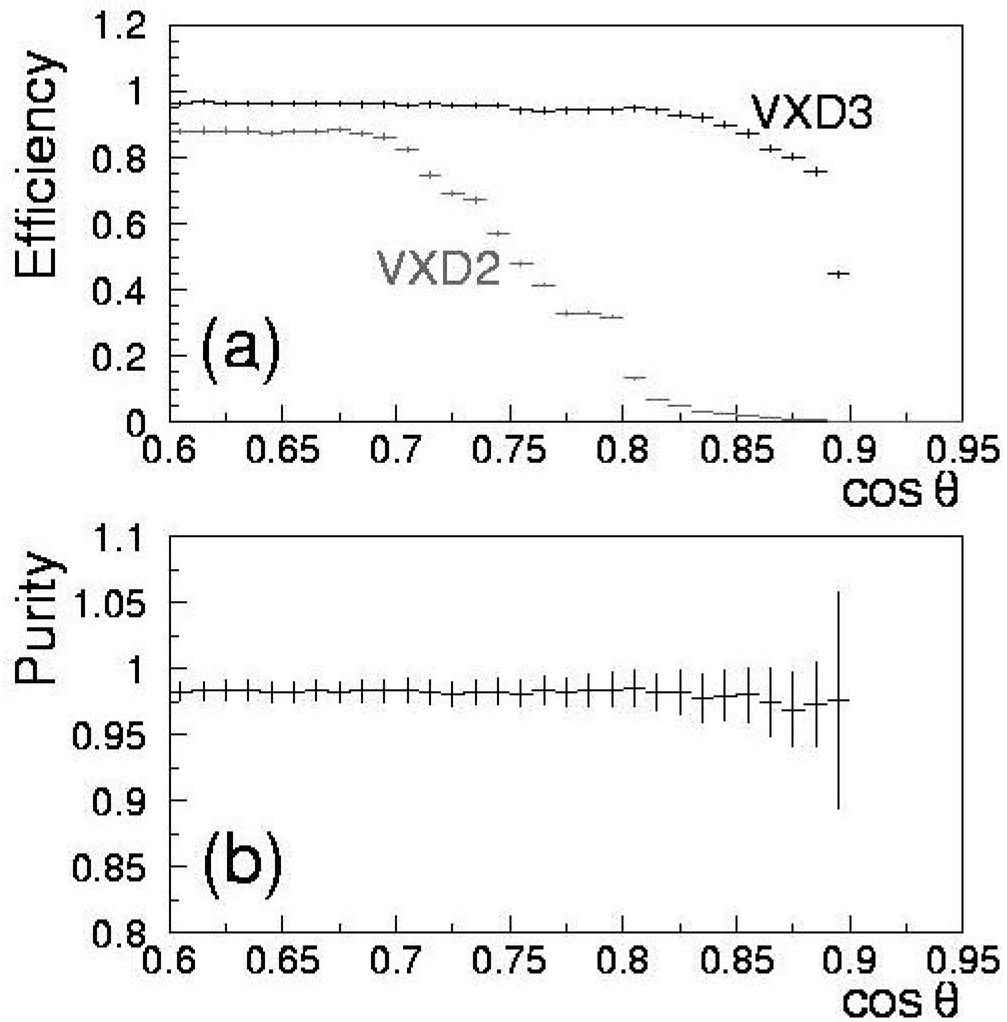
VXD3 Purity and Efficiency

CCD Vertex Detectors

b tagging efficiency and purity

includes two layer tracks



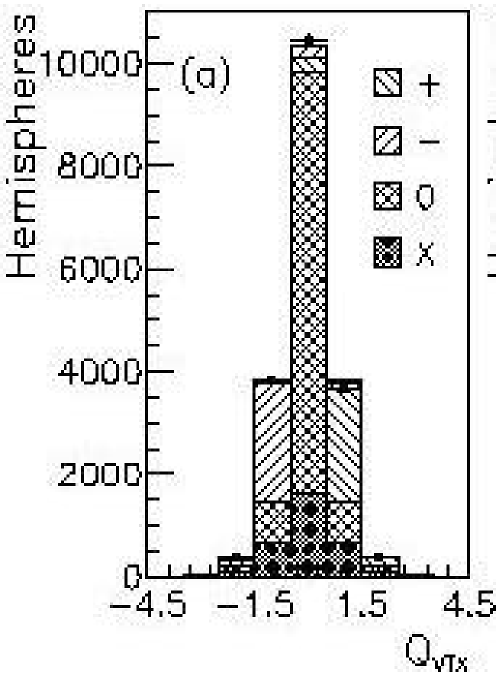


Jet Charge

CCD Vertex Detectors

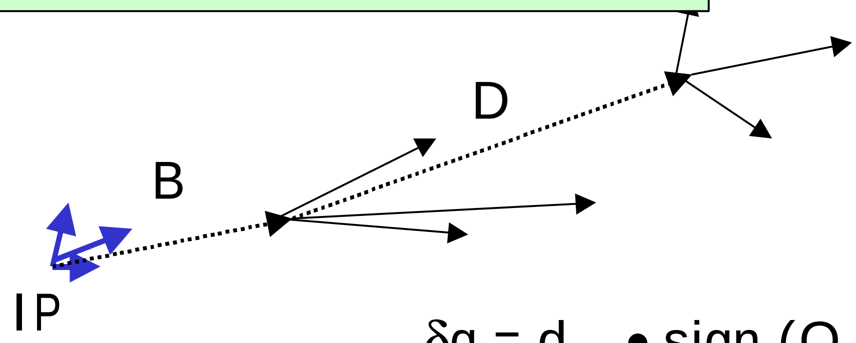
Precision Vertexing, with complete decay reconstruction, leads to discrimination between B^+ and B^-

VXD3 at SLD



Dipole Charge

CCD Vertex Detectors

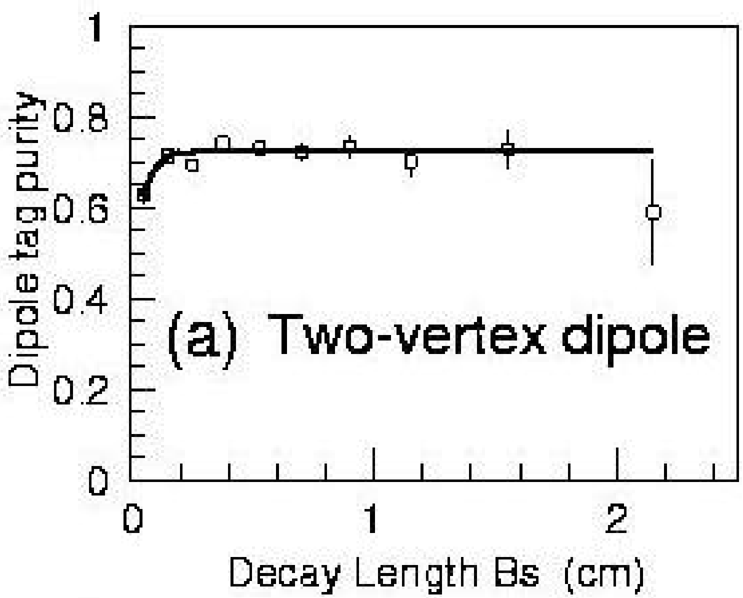


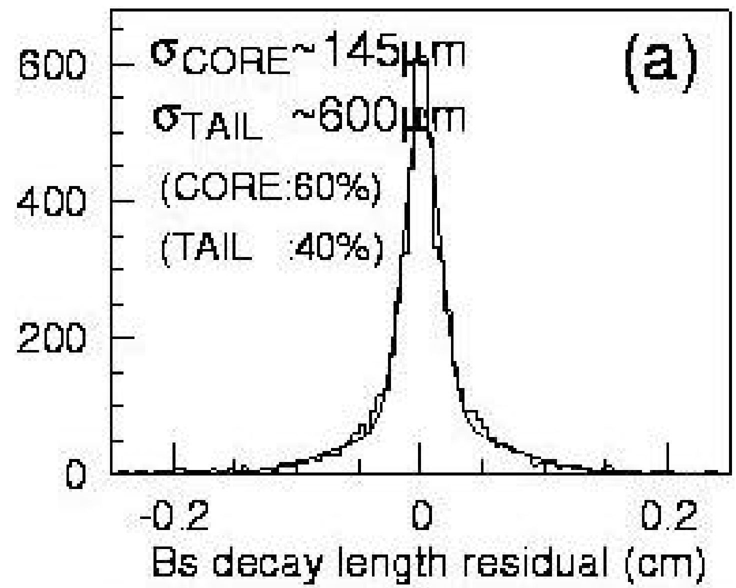
dipole charge separates B from $\bar{B}$

$$\delta q = d_{BD} \bullet \text{sign}\,(Q_D - Q_B)$$

$b \rightarrow c$ (dq positive)

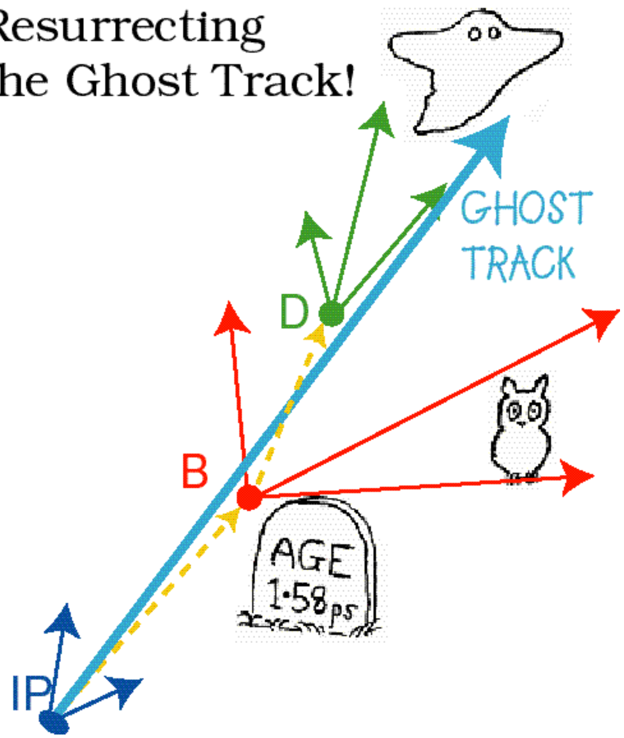
$\bar{b} \rightarrow \bar{c}$ (dq negative)





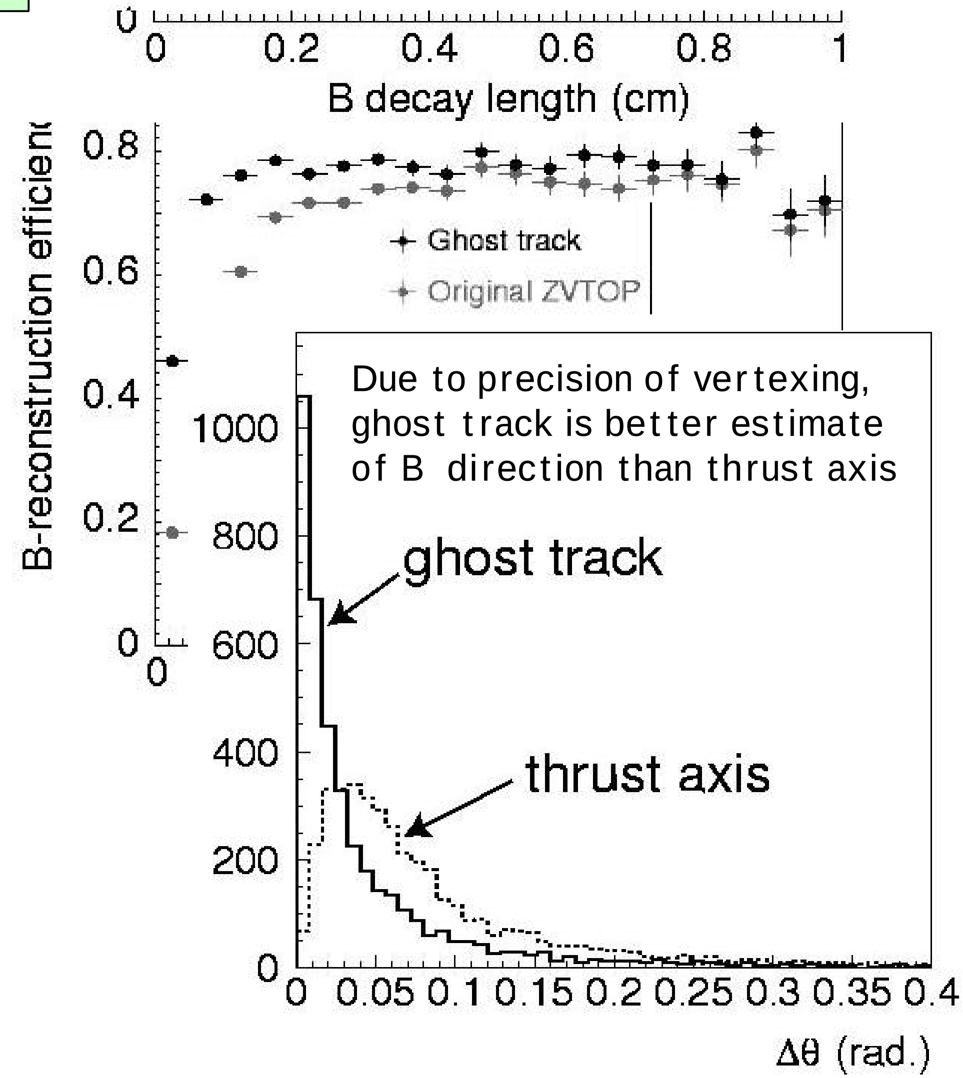
Ghost Track

Resurrecting
the Ghost Track!



T. Abe

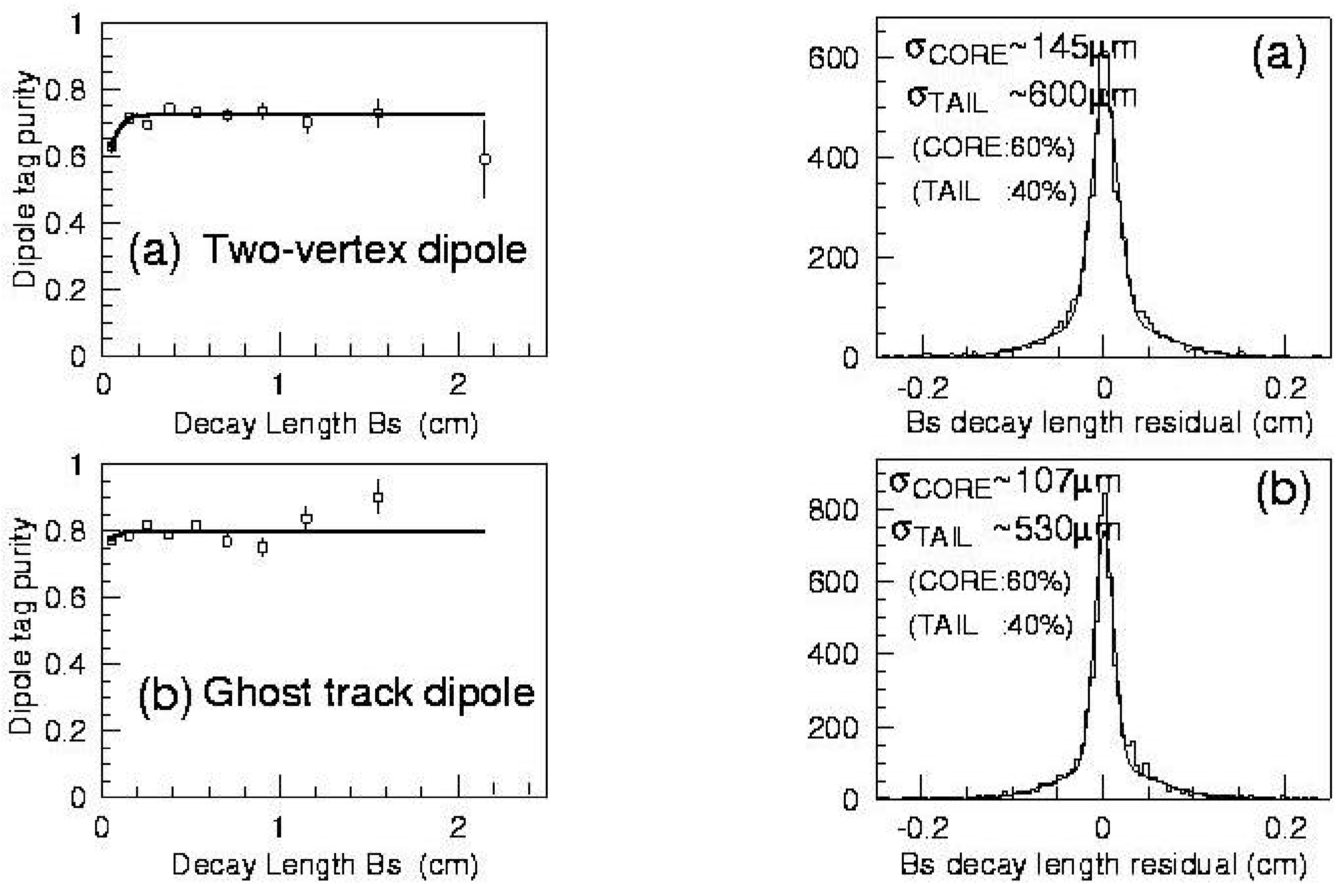
CCD Vertex Detectors



Charge Efficiency and Decay Length Resolution

CCD Vertex Detectors

Ghost track method improves dipole charge tag and decay length resolution



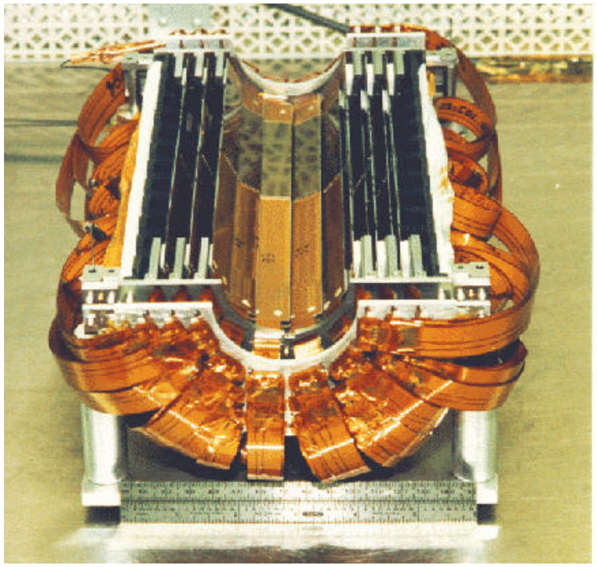
Lesson on Ultimate Performance

CCD Vertex Detectors

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 μm point resolution throughout the entire system
7.8 μm impact parameter resolution at high energy



Recap of CCD Advantages

High granularity

20 x 20 x 20 μm^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 x 16 mm^2 at SLD

facilitates ease of geometry

Exceptional system-level performance demonstrated

well matched to Linear Collider

The Next Generation

CCD Vertex Detectors

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

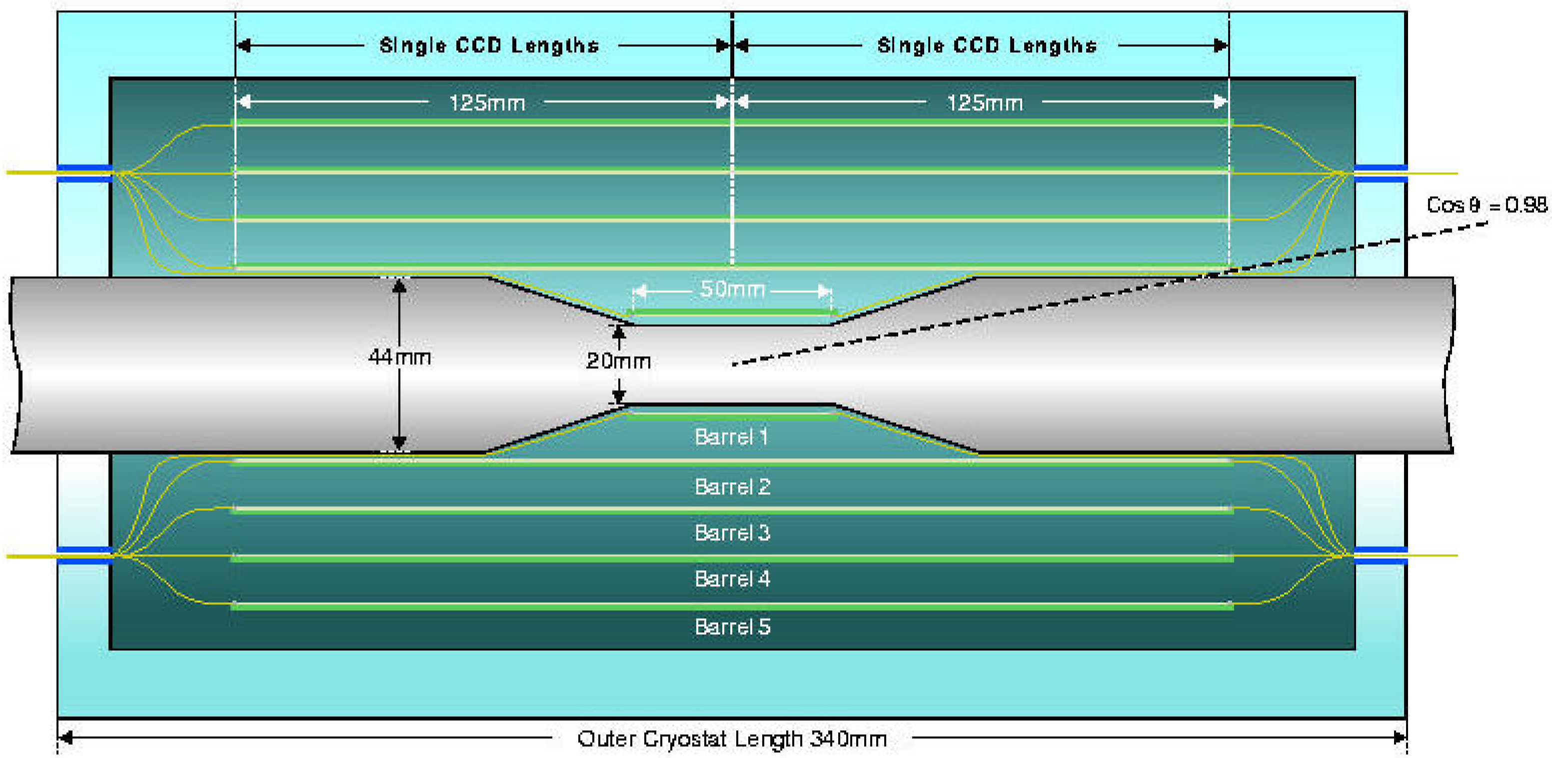
⇒ radiation immunity
  * design shielding to protect CCDs
  * improve CCD tolerance to radiation

Vertex Detector Design for the future Linear Collider

- Maximum Precision (< 4 μm)
- Minimal Layer Thickness
  (1.2% X_0 → 0.4% X_0 → 0.12% X_0 → 0.06% X_0)
  SLD-VXD2 SLD-VXD3 Linear Collider stretched
- Minimal Layer 1 Radius (28 → 12 mm → 5mm)
  SLD-VXD3 LC Schumm challenge
- Polar Angle Coverage (cos θ~ 0.9)
- Standalone Track Finding (perfect linking)
- Layer 1 Readout Between Bunch Trains
- Deadtime-less Readout

Proposed Design for Future Linear Collider

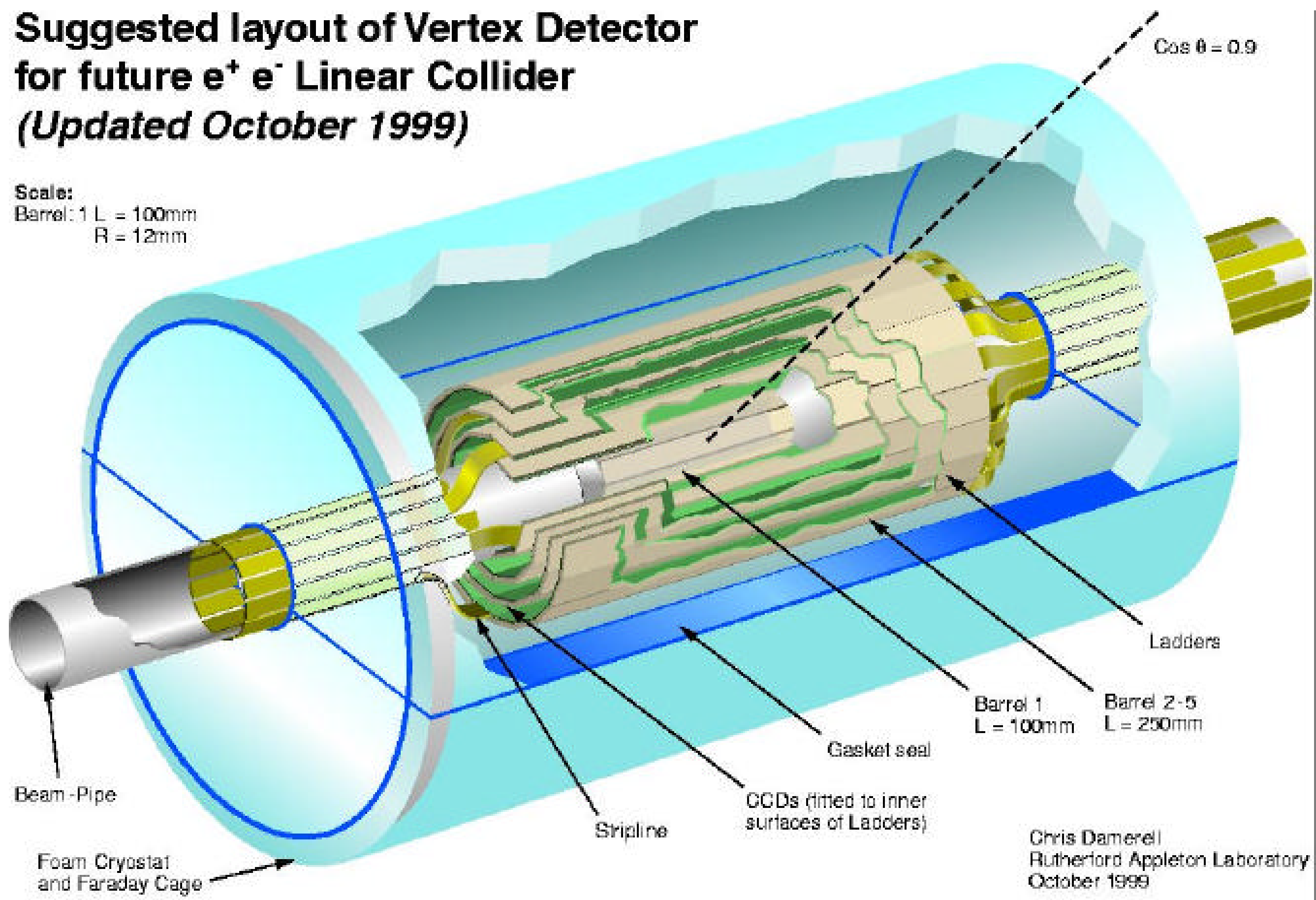
CCD Vertex Detectors



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

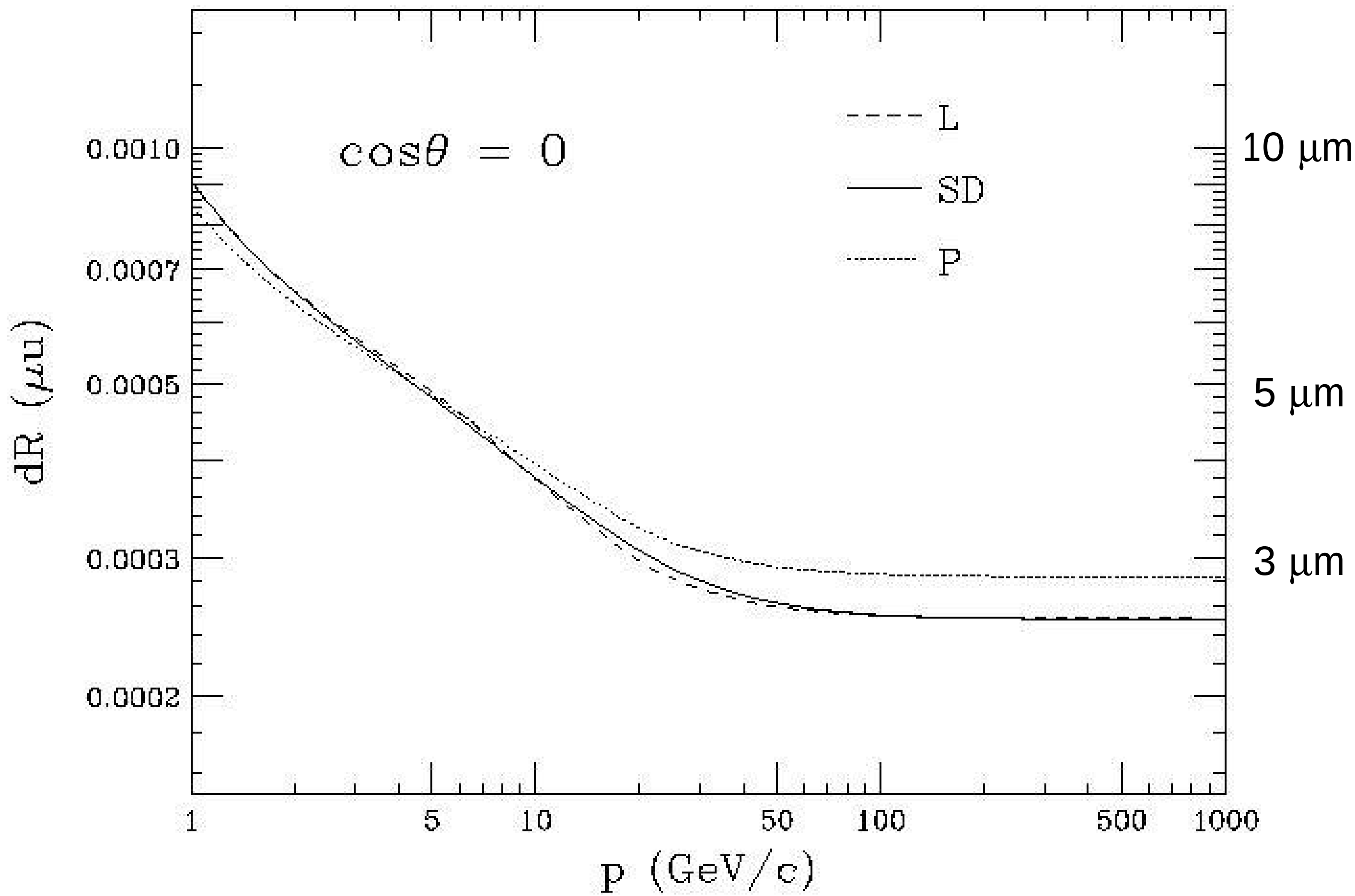
TESLA Proposal

CCD Vertex Detectors



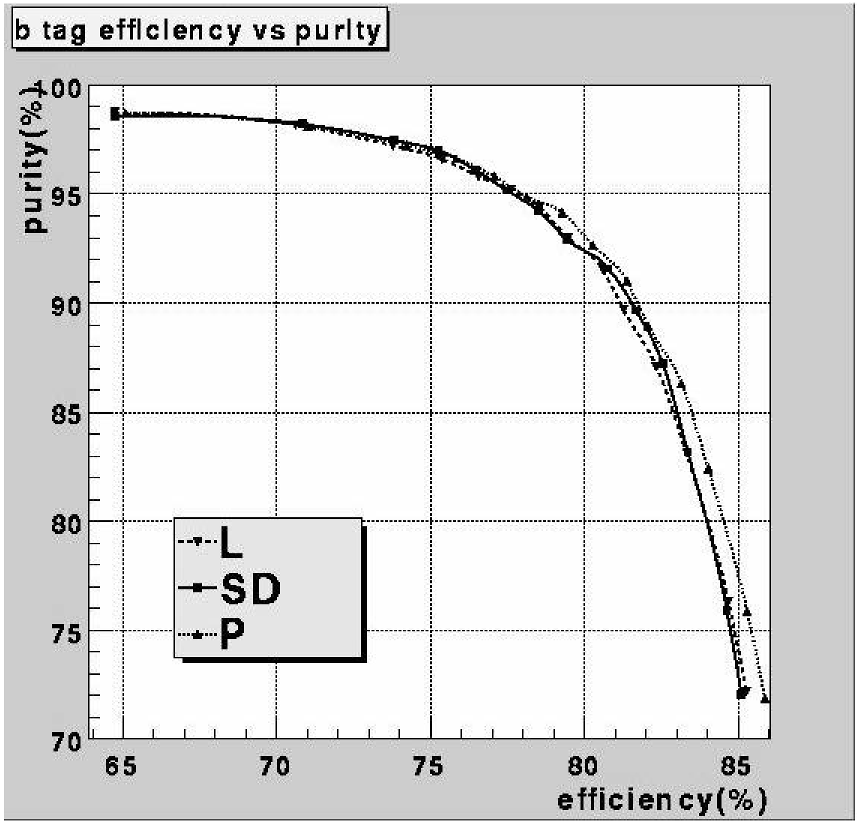
Impact Parameter Resolution of LC Proposal

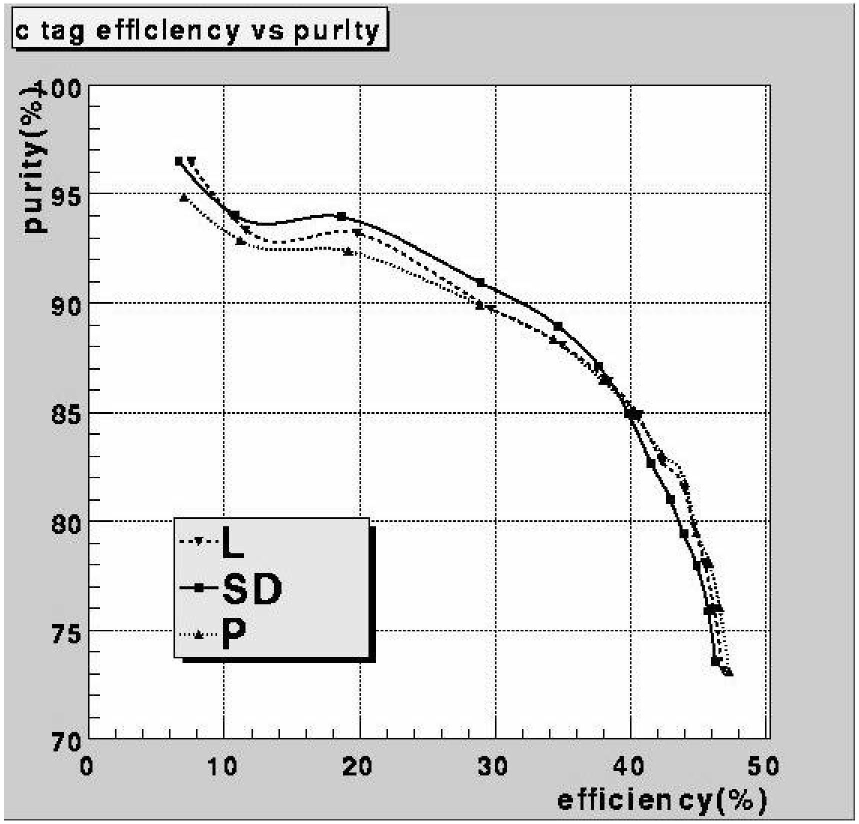
CCD Vertex Detectors



Tagging Performance of LC Proposal

CCD Vertex Detectors





Radiation Hardness

CCD Vertex Detectors

<u>Surface Damage</u> from ionizing radiation

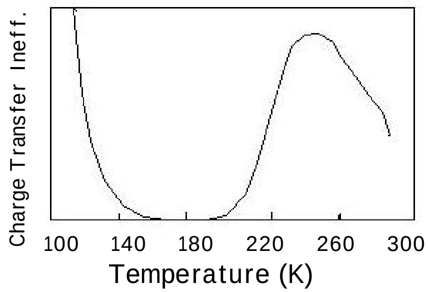
hard to > 1 Mrad (acceptable for LC)

<u>Bulk Damage</u>

results in loss of charge-transfer efficiency (CTE)

<u>ionizing radiation</u>

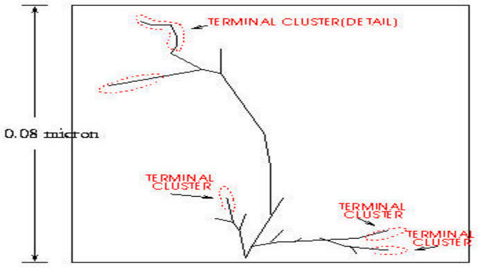
damage suppressed by reducing the operating temperature



<u>hadronic radiation (neutrons)</u>

damage clusters → complexes

cooling much less effective



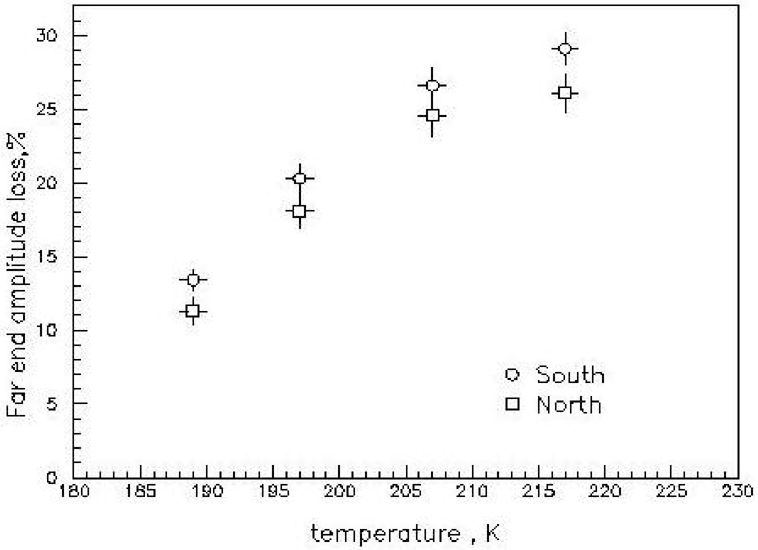
VXD3 Experience on Radiation Damage

CCD Vertex Detectors

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 (≈220 K).
Reducing to 190 K ameliorated the damage

There is a strong temperature dependence to the effect of exposure



Neutron Damage

Background estimates for the next Linear Collider
have varied from 10^7 n/cm^2/year to 10^{11} n/cm^2/year

- 2.3 x 10^9 n/cm^2/year (Maruyama-Berkeley2000)

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

<u>Increase tolerance to neutrons can be achieved through</u>

- 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	~ 2×10^9 n/cm^2, $T_{room,}$ Pu(Be),≈ 4 MeV
@SLAC	Annealing study 100° C for 35 days
@Reactor (I)	~ 2×10^9 n/cm^2, $T_{room,}$ reactor*, ≈ 1 MeV
@Reactor (II)	~ 1.2×10^9 n/cm^2 , T~190K, reactor* , ≈ 1 MeV

Total exposure ~ 5.2×10^9 n/cm^2

IEEE Trans. Nucl. Sci. 47, 1898 (2000)

Neutron Damage and Amelioration Study

CCD Vertex Detectors

Image of damaged sites

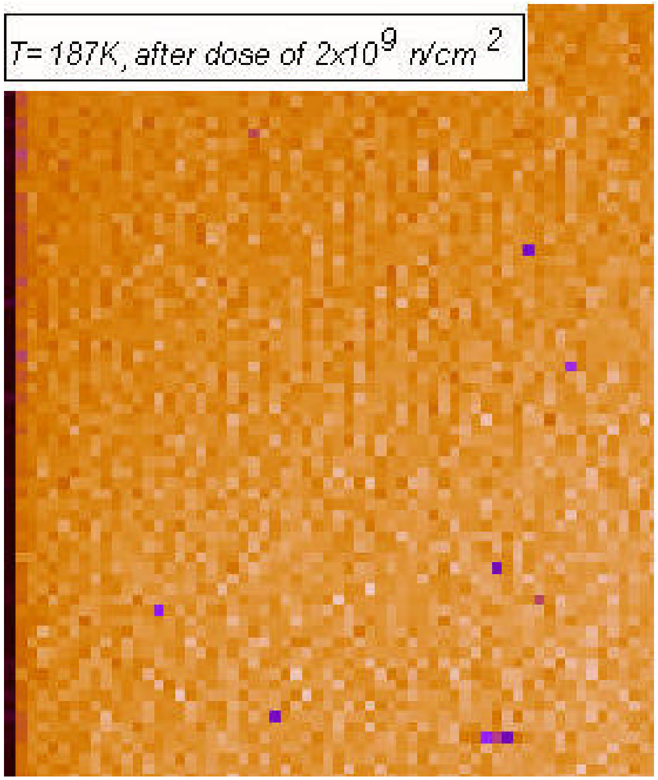
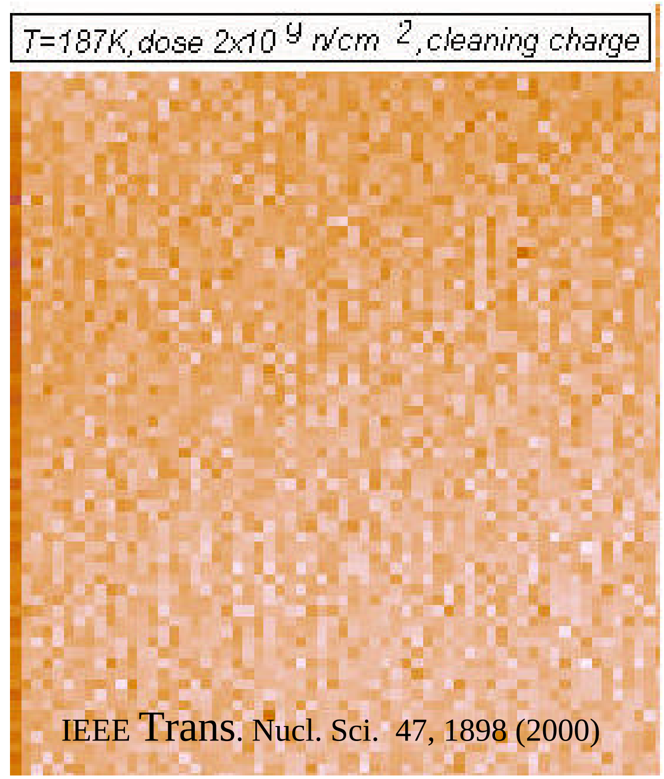


Image of damaged sites after flushing



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

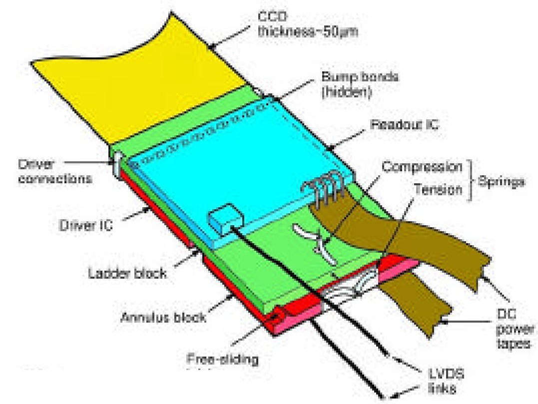
Other Development Directions

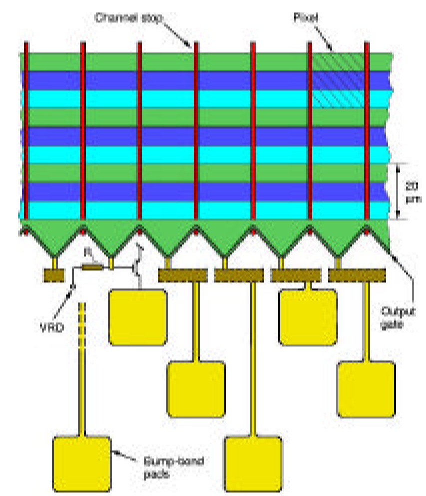
CCD Vertex Detectors

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

JLC - room temperature operation for JLC
- motivated to eliminated cryogenics

TESLA - column parallel readout
and 50 MHz readout
- reduce build-up of background hits
during bunch train





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2. T. Abe, "Current Performance of the SLD VXD3," Nucl. Inst. and Meth. A447, 90 (2000).

3. D.J. Jackson, Nucl. Inst. and Meth. A388, 247 (1997).

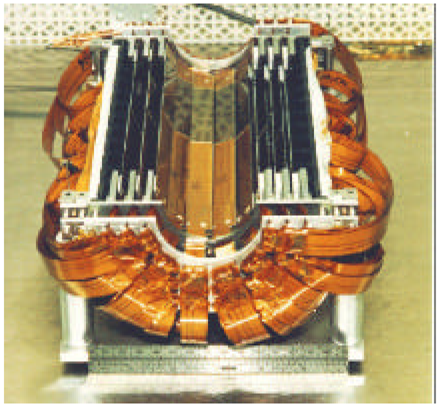
4. C.J.S. Damerell, "Charge-coupled devices as particle tracking detectors," Rev. Sci. Inst. 69, 1549-1573 (1998).

Conclusion

CCD Vertex Detectors

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,
  eg. $Bs \rightarrow DsX$ ($Ds \rightarrow \varphi\pi$))
- 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