Vertex Detector Issues for the LCD

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SLAC
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Physics of Linear Collider demands the <u>best possible</u> vertex detector performance

physics signals will be rich in sec. vertices
event rates will be limited

CCDs offer the most attractive avenue for achieving this performance (but rad-hardness must improve)

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

Active Pixels are being studied in Europe

Larger material thickness (hybrids)
Monolithic APDs also being developed
(http://hep.ph.liv.ac.uk/~green/lcfi/lcfihome.html)

Outline of Today's Presentation

⇒ Typical and Important Physics Processes
- Higgs, W pairs, ...

⇒ Detector Design
- Inner radius, magnetic field, #layers, etc.
- Cost exercise

⇒ Radiation environment
- Expected backgrounds
- Radiation damage studies
  - neutron induced damage

⇒ Simulation Study Plans
- optimized detector design
- physics demands

The Vertex Detector will impact most of the physics topics of the LC. For example:

Higgs

- branching ratios critical test of SM
  (or measurement of tan β)
- Higgs self-couplings (Zhh)

SUSY Higgs

- A -> τ τ

Supersymmetry

- staus (flavor-dependence of SUSY breaking)

Top

- mass, width, etc.
- Yukawa couplings

W pairs

- W's with flavor tagging
- W/Z discrimination through flavor tagging,
  or improved mass resolution

Z´

- tau polarization

Z Pole

- Rb, Ab, B pairs, τ pairs,

$e^+e^- \to \underset{\downarrow \atop q\bar{q}}{Z}\, H_{\hookrightarrow b\bar{b}}$ (4 jet topology) at $\underline{500\ \text{GeV}}$ w/ $\underrightarrow{10\ \text{fb}^{-1}}$

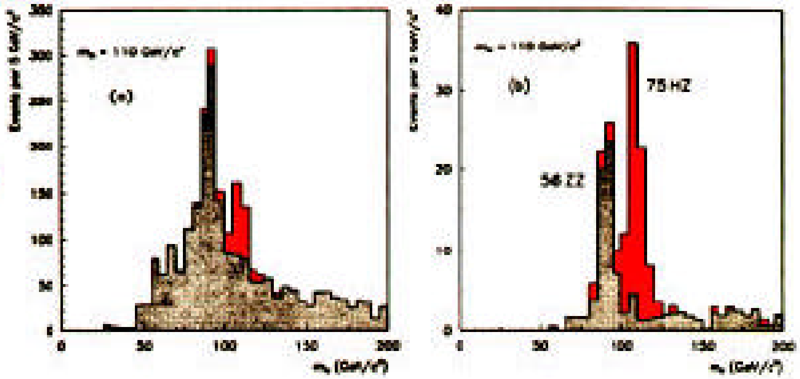
$(\sim\frac{1}{5}$ NLC yr$)$

1. $\equiv 4$ jets w/ $M_{jet} < 45$ GeV $(e^+e^- \not\to q\bar{q})$
2. $E_{tot} > 0.7\sqrt{s}$ $(\gamma\gamma)$
3. $\chi^2_{WW} > 5$ (fit) (WW)
4. $M_{ij} \sim M_Z$ (80-125 GeV)

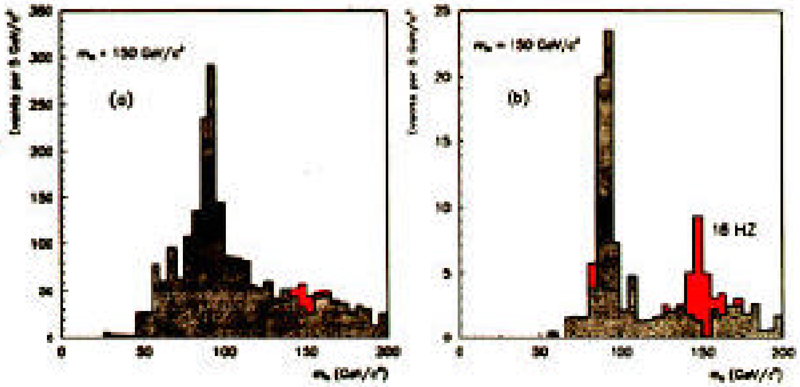
no b tag

$b\bar{b}$ tag

$M_H = 110\ \text{GeV}/c^2$ ↳



$M_H = 150\ \text{GeV}/c^2$ ↳



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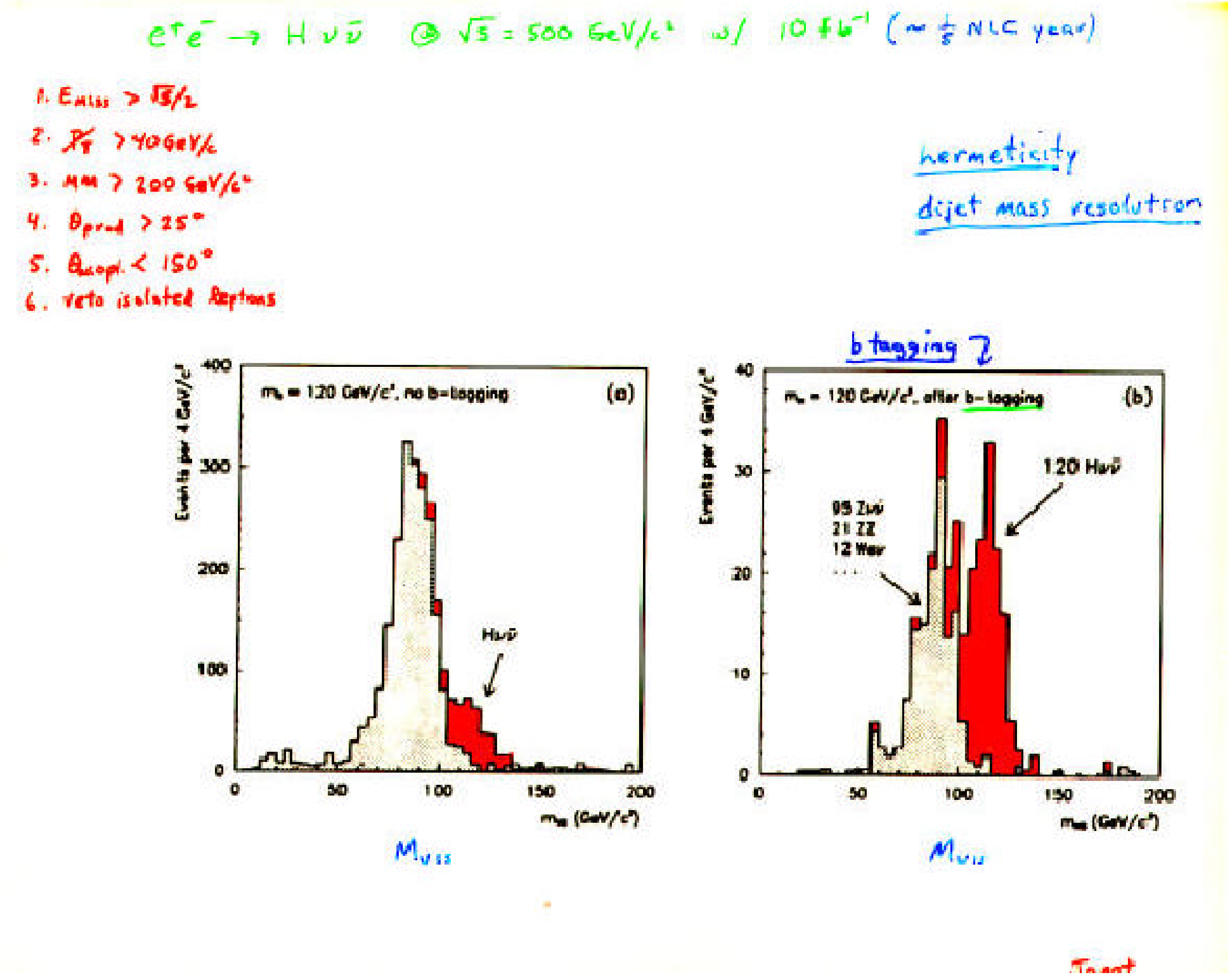


$e^+e^- \to H\nu\bar{\nu}$ @ $\sqrt{s} = 500$ GeV/c^2 w/ 10 fb^{-1} (~ $\frac{1}{5}$ NLC year)

1. $E_{miss} > \sqrt{s}/2$
2. $\not{p}_T > 40$ GeV/c
3. MM > 200 GeV/c^2
4. $\theta_{prod} > 25°$
5. $\theta_{acopl.} < 150°$
6. veto isolated leptons

hermeticity

dijet mass resolution

b tagging ?

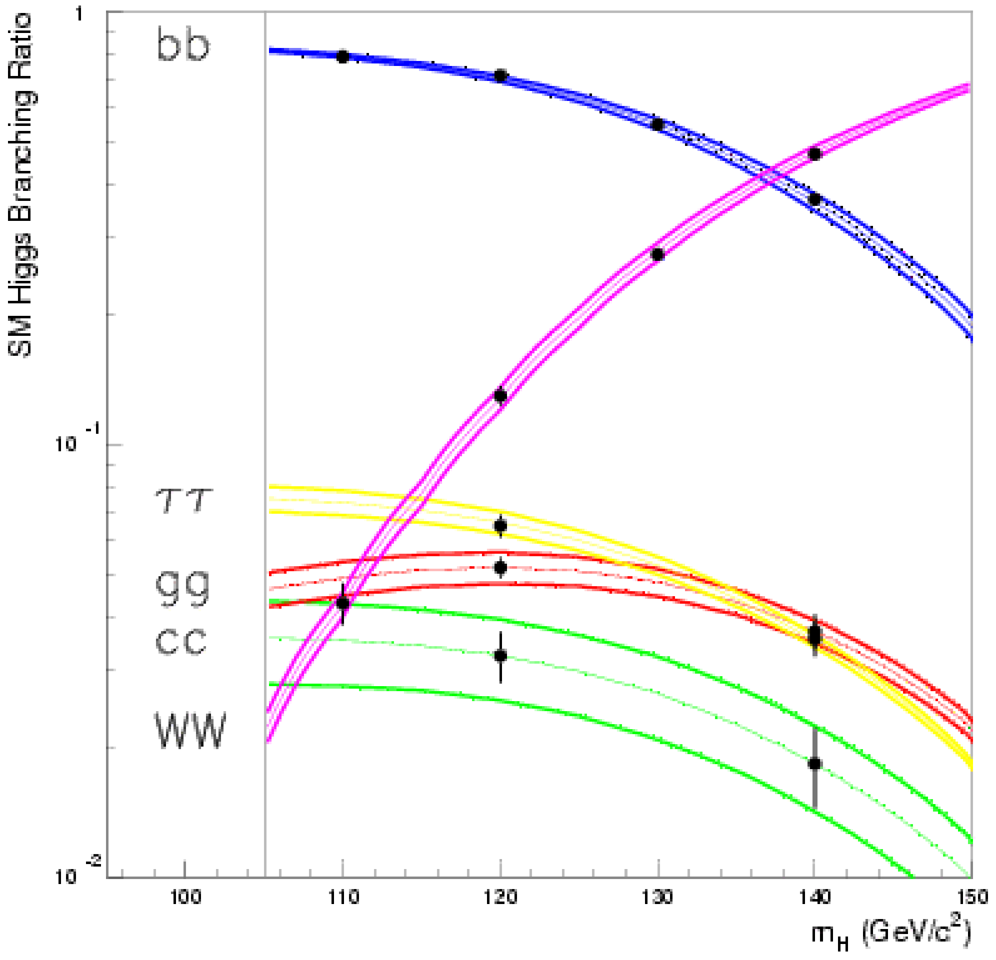


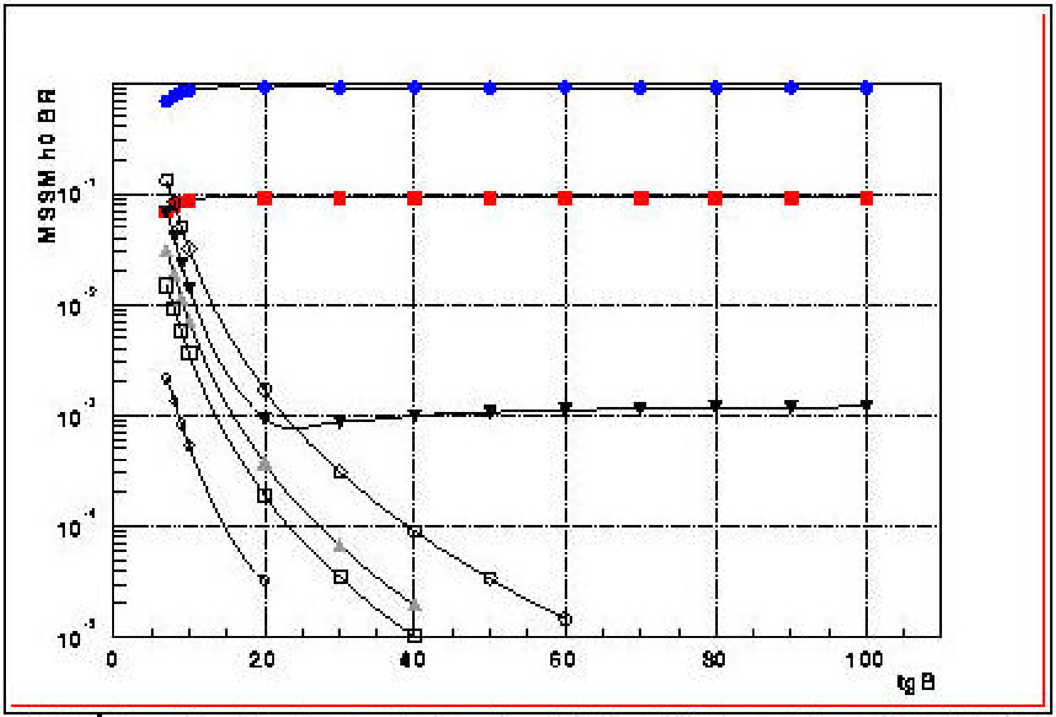
Figure 5: Determination of Higgs boson branching ratios in a variety of decay modes, from [66 The error bars show the expected experimental errors for 500 fb^{-1} at 350 GeV. The bands sho the theoretical errors in the Standard Model predictions.

Battaglia

MSSM h^0 Branching Ratios vs $tg\beta$: Maximal Mixing

Chris Potter

August 11, 2000



MSSM h^0 Branching Ratios vs $tg\beta$ Assuming Maximal Mixing and m_{h^0}=120 GeV (solid ○=bb, solid square=$\tau\tau$, solid Δ=cc, solid ∇=gg, ○=ww, square=ss, Δ=tt $\diamond$=$\gamma\gamma$)

Studies now underway (that I am aware of):

Higds branching ratios

Higgs branching ratios
  - SM, SUSY, vertex optimization
    Iwasaki, Potter, Sinev

Top quark reconstruction (vertexing/calorimetry issues)
    Iwasaki

Charm tagging to enhance
    Strong Symmetry Breaking Sensitivity
  - aggressive scenarios
    Walkowiak, Schumm

Radiation backgrounds and masks
    Maruyama, Markiewicz, et al.

Installation of ZVTOP into LCD software
  - ROOT - Abe, Iwasaki, Neal
  - JAS - Walkowiak, Schumm

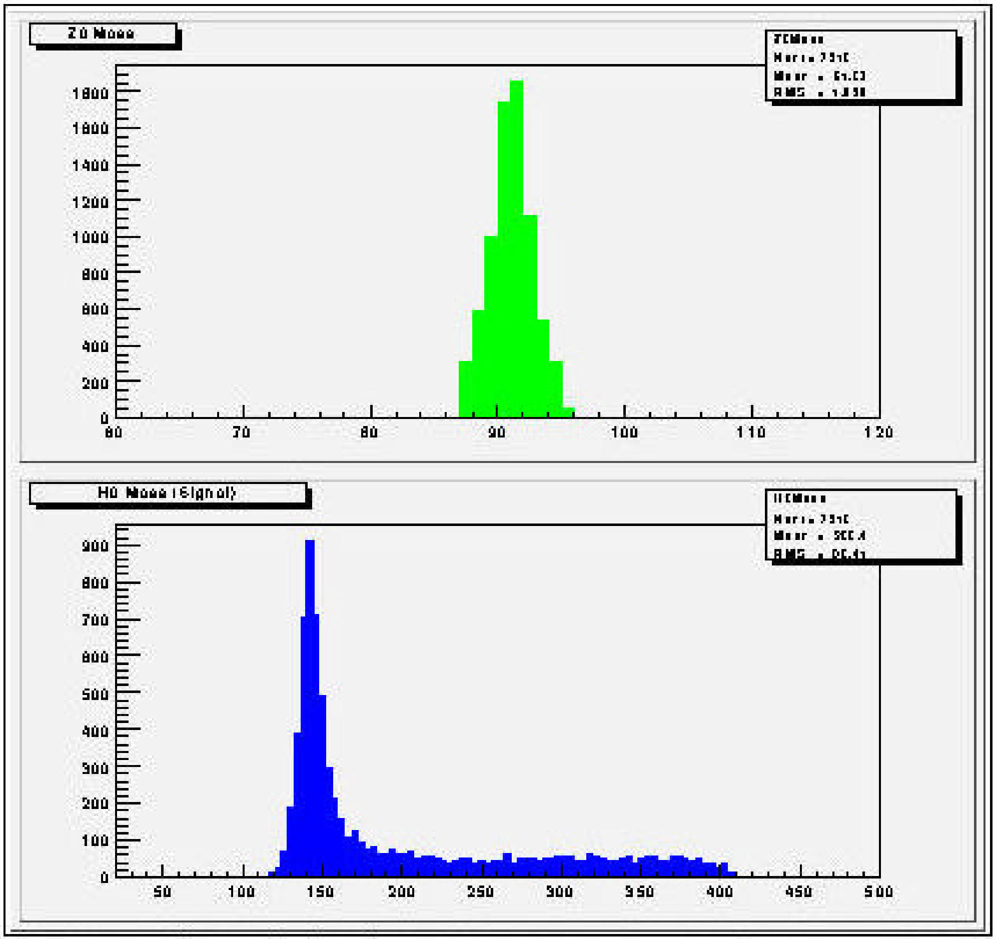
These studies are needed to justify our choice of vertex detector parameters.

Others?

$Z^0 \to l^+l^-$ Tag For $e^+e^- \to H^0Z^0$ Events

Chris Potter

August 28, 2000



Results for 10000 $e^+e^- \to H^0Z^0 \to e^+e^-$ events. Here $m_{\rm Higgs}$ = 140 GeV and $E_{\rm cms}$ = 500 GeV. The Z^0 mass cut is 3 GeV.

Critical Issues in Optimizing Flavor Tag:

⇒ track resolution
  * determined by technology:
    CCDs offer very best resolution
      (but, how good can it be,
      AND what do we need?)

⇒ outer radius of vertex detector
  * constrained by outer detector & budget
    compact, conventional, ??

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

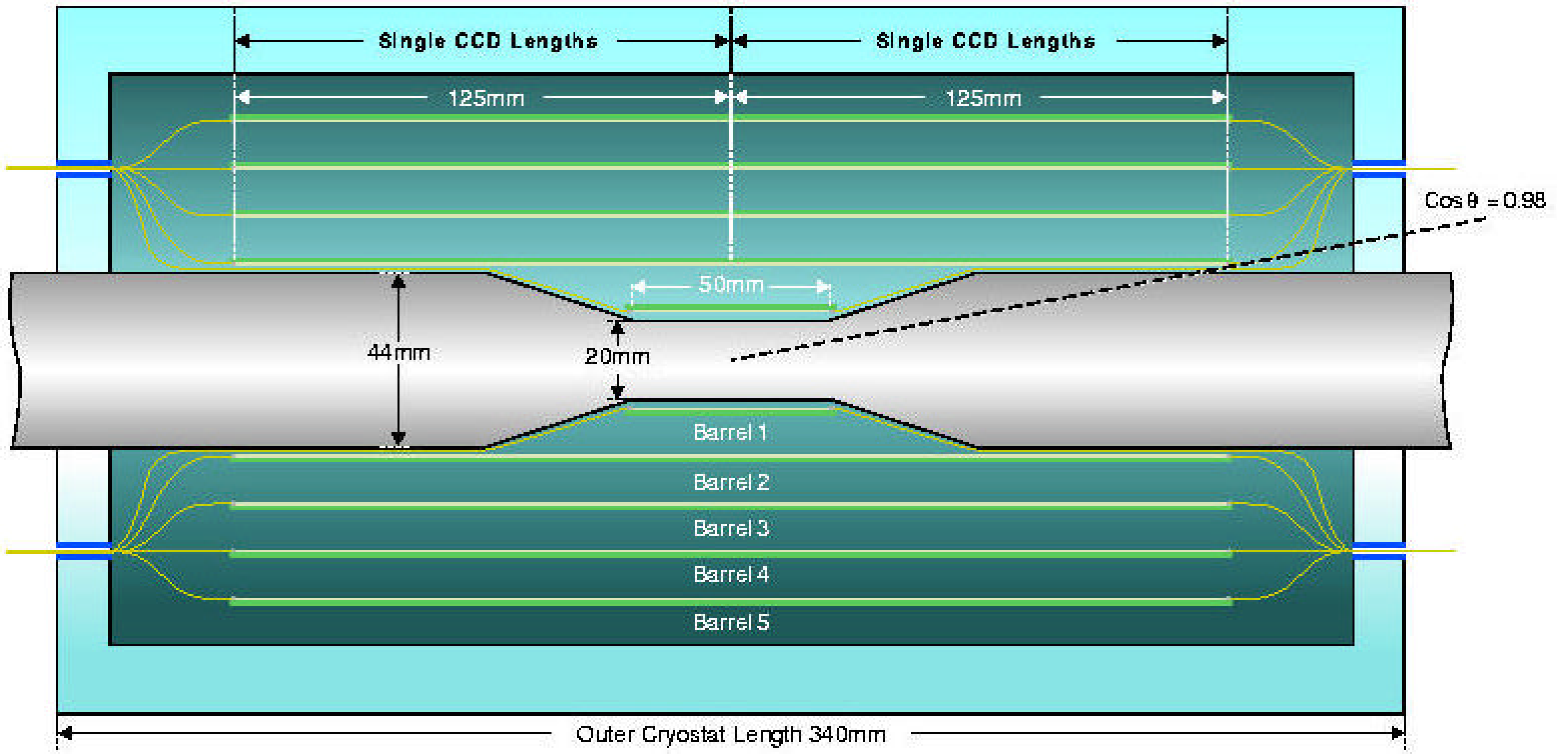
⇒ radiation immunity
  * design shielding to protect CCDs
  * improve CCD radiation tolerance

Vertex Detector Design

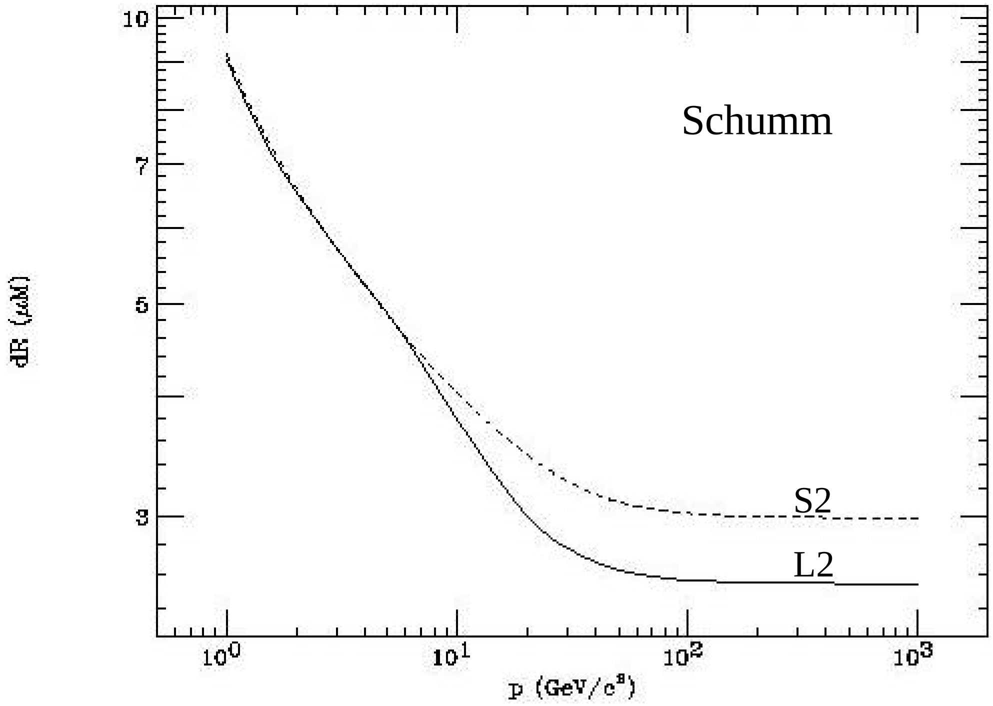
for the future Linear Collider

- 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 → 12 mm → 5mm)
  SLD-VXD3 LC Schumm challenge
- Polar Angle Coverage ($\cos\theta \sim 0.9$)
- Standalone Track Finding (perfect linking)
- Layer 1 Readout Between Bunch Trains (4.6 msec)
- Deadtimeless Readout (high trigger rate)

Suggested layout of Vertex Detector for future $e^+ e^-$ Linear Collider (Updated November 1998)



Vertex Detector Resolution



Cost Estimate Exercise (April/May, 2000)

The VXD3 cost, including contingency, was 1997 k$ (FY95)

5 barrel LCD detector was estimated to be 3973 k$ (FY00), without contingency (40%).

Engineering manpower	900k$
Electronics	500k$
Mechanics	573k$
CCD Detectors	2000k$

Note: this cost estimate does not include beam-pipe, installation, or contingency, which were included in VXD3. For the LCD, they are costed elsewhere.

Radiation Hardness Tests of CCDs

Nick Sinev

(http://blueox.uoregon.edu/~jimbrau/talks/IEEE-99/ieee99.pdf)

Background estimates 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 (C. Damerell)

We need to develop procedures
and designs to increase tolerance

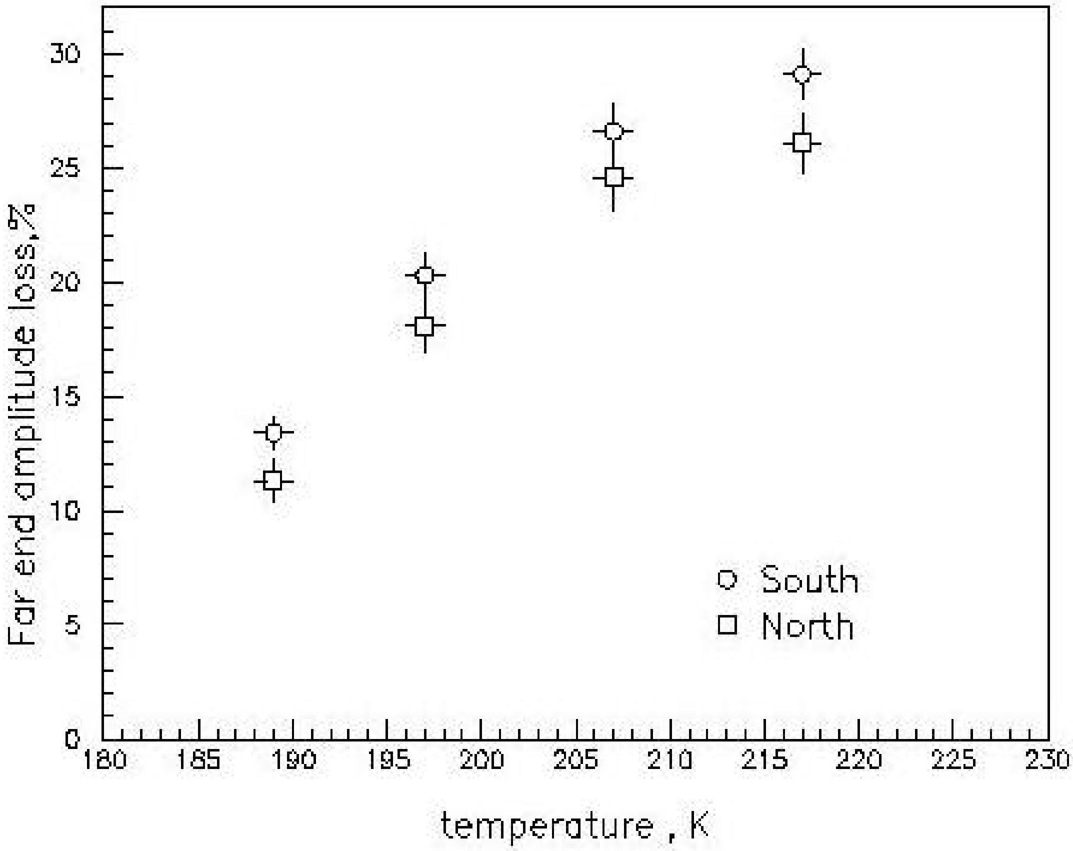
More radiation damage studies are called for
- improve understanding of issues and sensitivity
- improve radiation hardness
  - flushing techniques
  - supplementary channels
  - bunch compression & clock signal optimization

SLD experience during VXD3 commissioning,

an undamped beam was run through the detector, causing radiation damage in the innermost barrel.

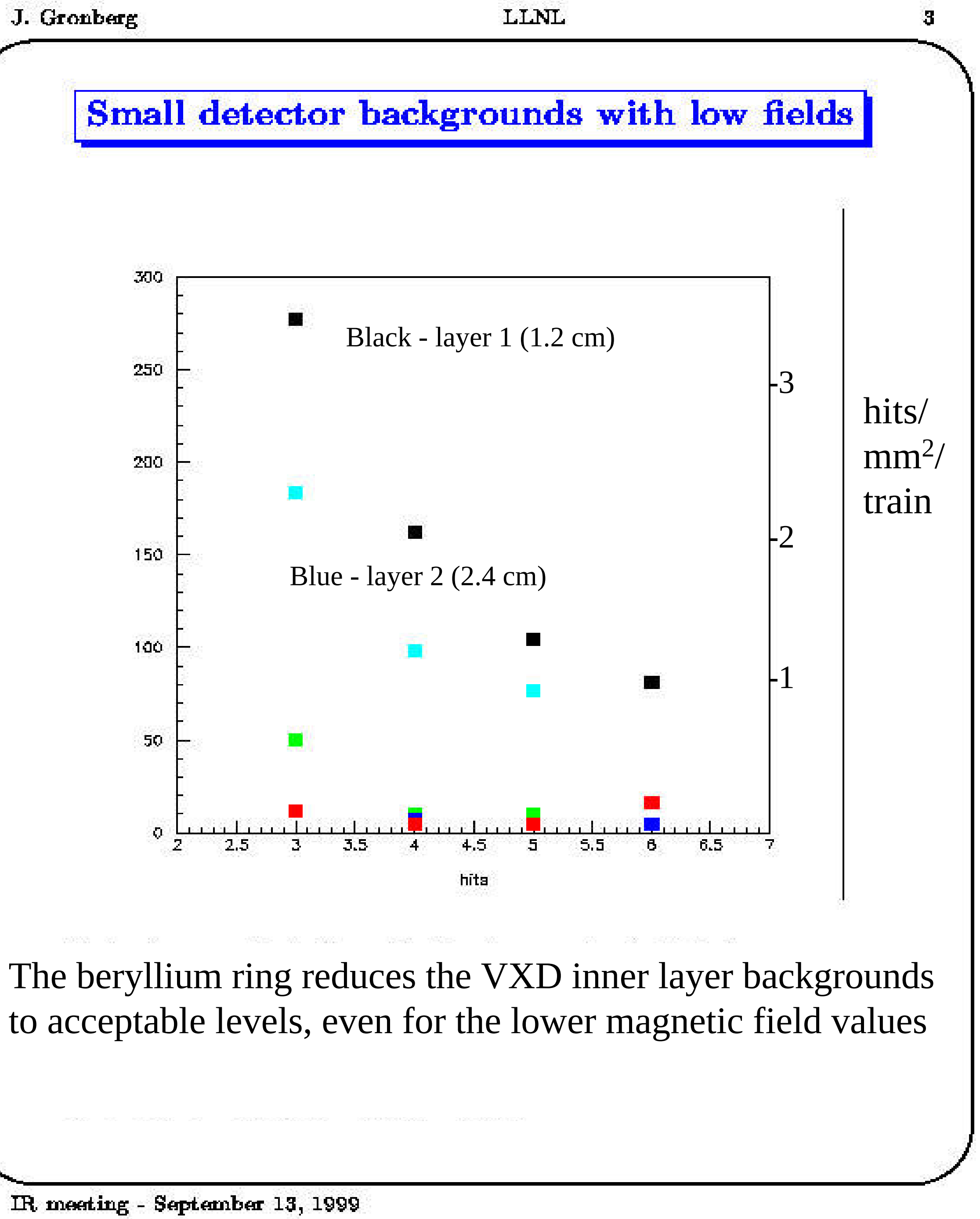
The damage was observed because we were operating the detector at an elevated temperature (≈220 K).

Reducing the temperature to 190 K ameliorated the damage



Signal loss during charge transfer from far region of the image due to radiation damage of CCDs as function of the CCD temperature

Thin beryllium rings along beam-line reduces backgrounds:



J. Gronberg LLNL 3

Small detector backgrounds with low fields

Black - layer 1 (1.2 cm)

Blue - layer 2 (2.4 cm)

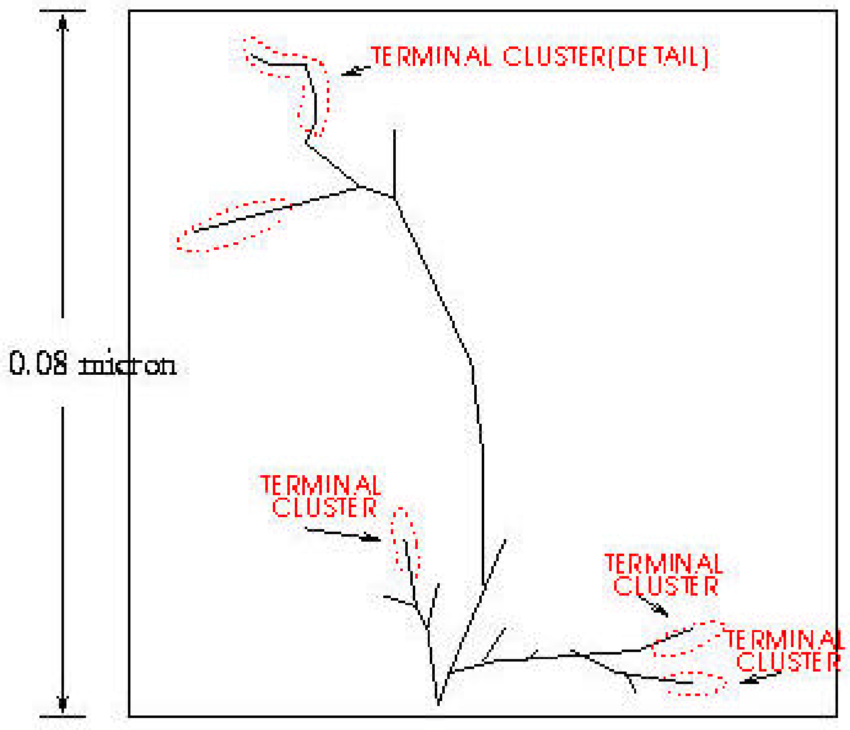
hits/
mm^2/
train

The beryllium ring reduces the VXD inner layer backgrounds to acceptable levels, even for the lower magnetic field values

IR meeting - September 13, 1999

Theory of Radiation Damage

The most important radiation damage in CCDs caused by heavy particles is displacement in the bulk silicon.
1 MeV neutrons can transfer up to 130 keV to PKA. Only 15 eV is needed to displace an atom from the lattice.



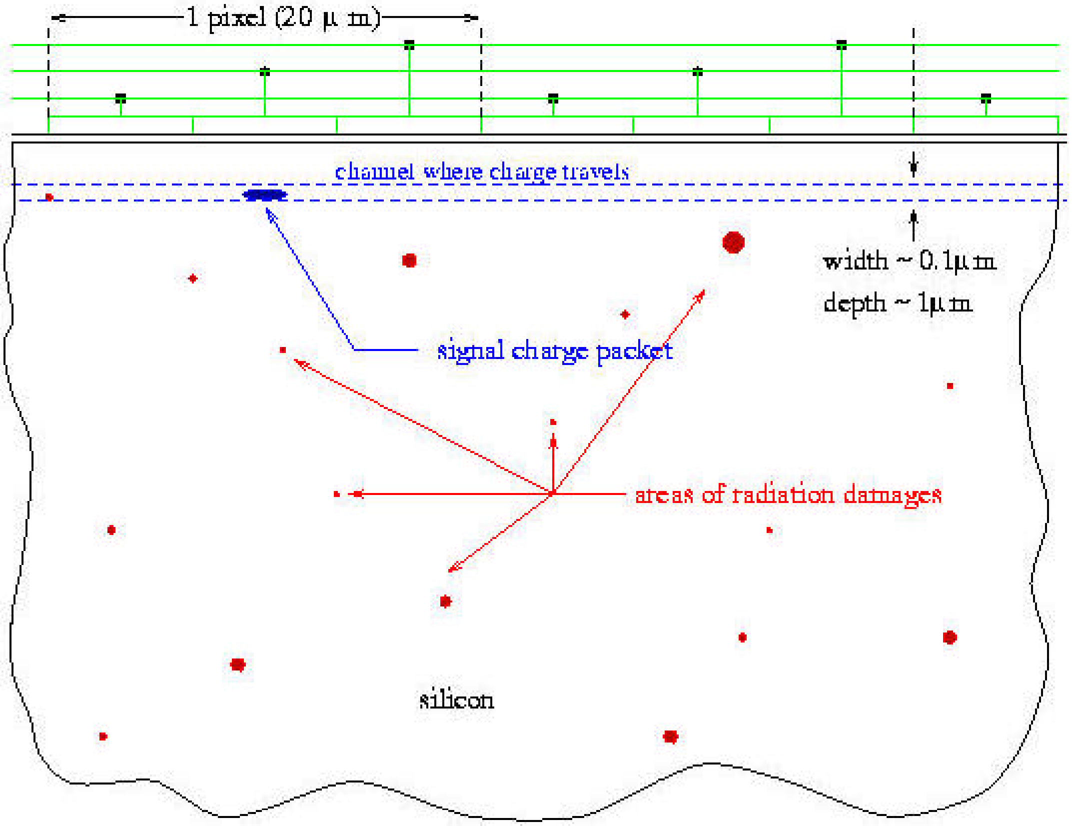
Example of simulated tracks of knock-out silicon atoms from a primary knock-out energy of 40 keV. (V.A.J.Van Lint, NIM A253, 453 (1987).)

Vacancy (V) and interstitial silicon (I) pairs are created as a result of atom displacement. More than 90% of such pairs recombine immediately. Those which are not recombined diffuse until they form complexes of two or more vacancies (V2 or V3) or vacancy-impurity (VP, V2O and so on). Such complexes are usually not mobile. Some of them are able to bind electrons, and the bound energy for some of these is about 0.35 - 0.5 eV below the conduction band. These may act as electron traps when empty. If the bound energy is close to the conduction band, (shallow traps) the lifetime of the bound state is so short, that the trapped electron will be released quickly and re-join the charge packet before the packet passes through the trap region. In this case no charge transfer inefficiency will be introduced by the defect.

However, for the deeper levels (close to 0.5 eV below the conduction band) the lifetime of the bound state, which is:

$$t = \frac{e^{(E_c - E_{tr})/kT}}{s_n c_n n_n N_c}$$

is larger than the inter-pixel transfer time , so trapped electrons are removed from the charge packet and released after the packet passes through the trap region. This leads to charge transfer inefficiency. Such inefficiency may be cured, however, by cooling the CCD to a low enough temperature, that the lifetime of the bound electrons in the trap becomes very long, so that the filled traps remain occupied when the next charge packet passes. Filled trap can't capture more electrons, so this trap will not lead to charge transfer inefficiency.



Microscopic picture of radiation damaged CCD

History of Exposures

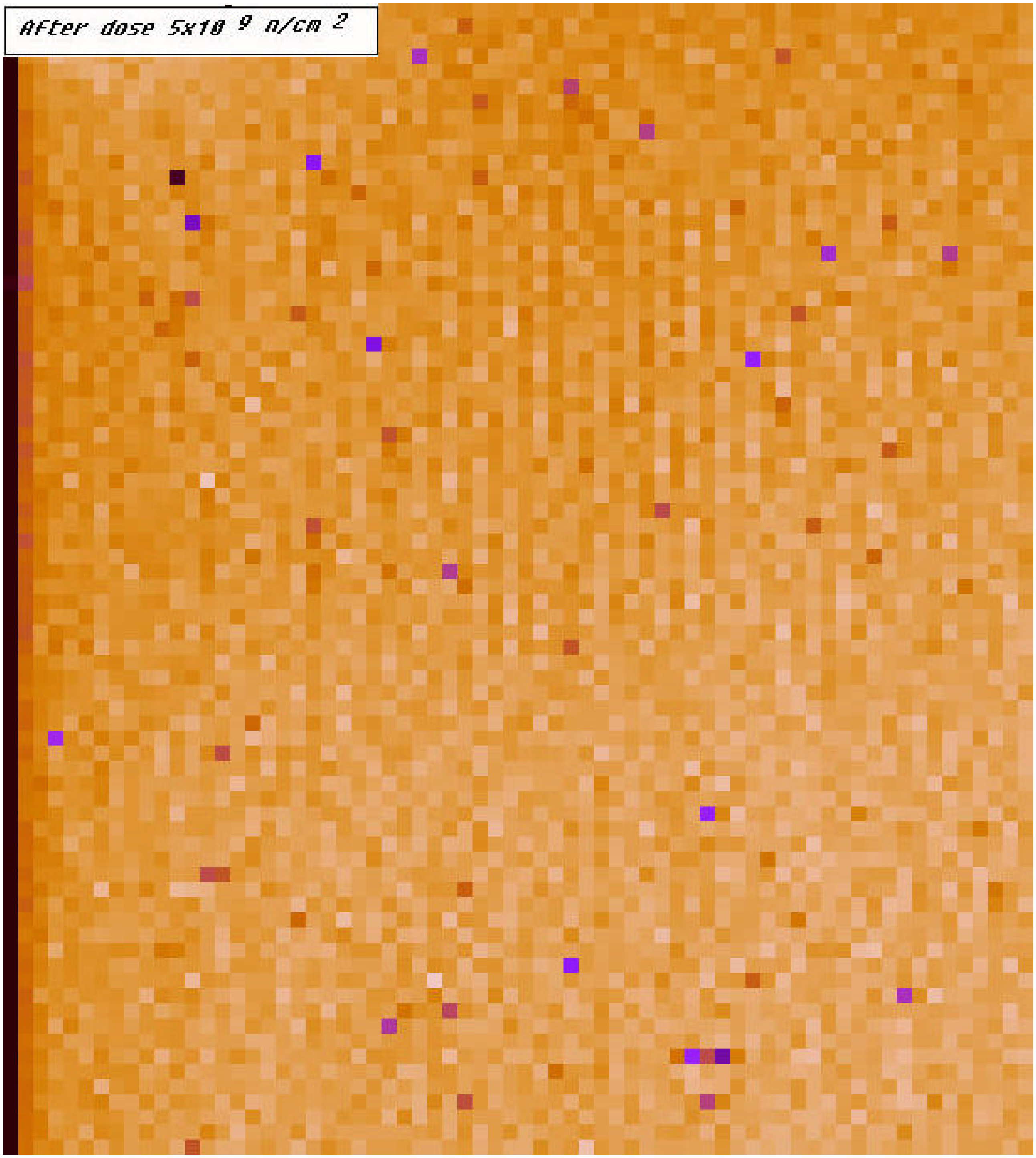
(spare SLD VXD3 CCD)

@SLAC	$\sim 2 \times 10^9$ n/cm^2 Pu(Be) $\langle E_n \rangle \approx 4$ MeV	room temperature
@SLAC	Annealing study	100° C for 35 days
@Reactor (I)	$\sim 2 \times 10^9$ n/cm^2 reactor* neutrons $\langle E_n \rangle \approx 1$ MeV ($\sim 1 \times 10^9$ n/cm^2 lower energy)	room temperature
@Reactor (II)	$\sim 1.2 \times 10^9$ n/cm^2 reactor* neutrons $\langle E_n \rangle \approx 1$ MeV ($\sim 1 \times 10^9$ n/cm^2 lower energy)	dry ice cooled (~190K)

Total exposure $\sim 5.2 \times 10^9$ n/cm^2

mix of source and reactor

* UC Davis (G. Grim et al)

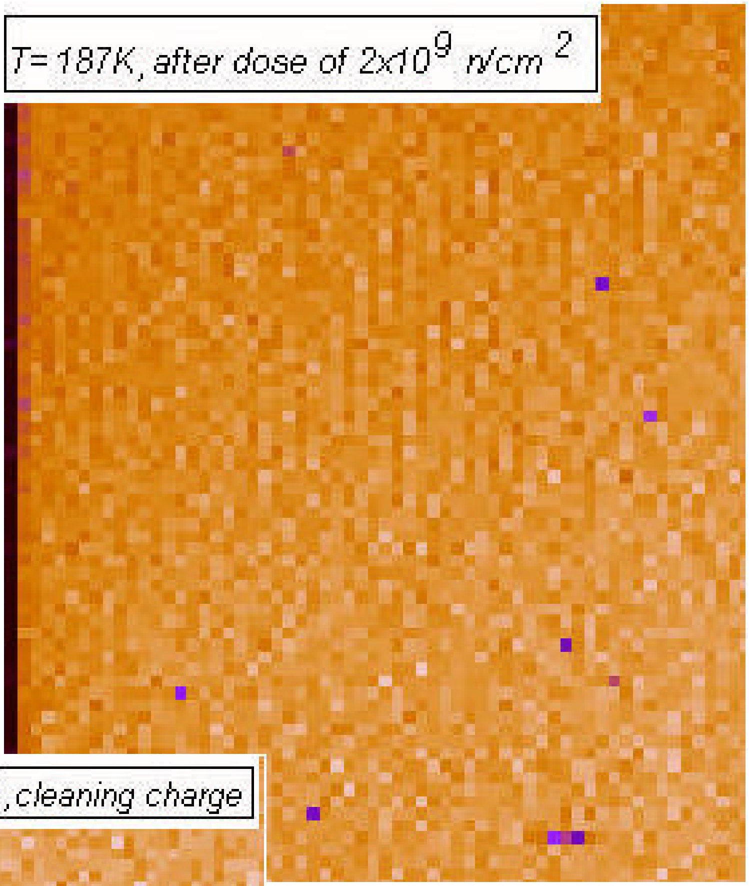

After dose 5x10 9 n/cm 2

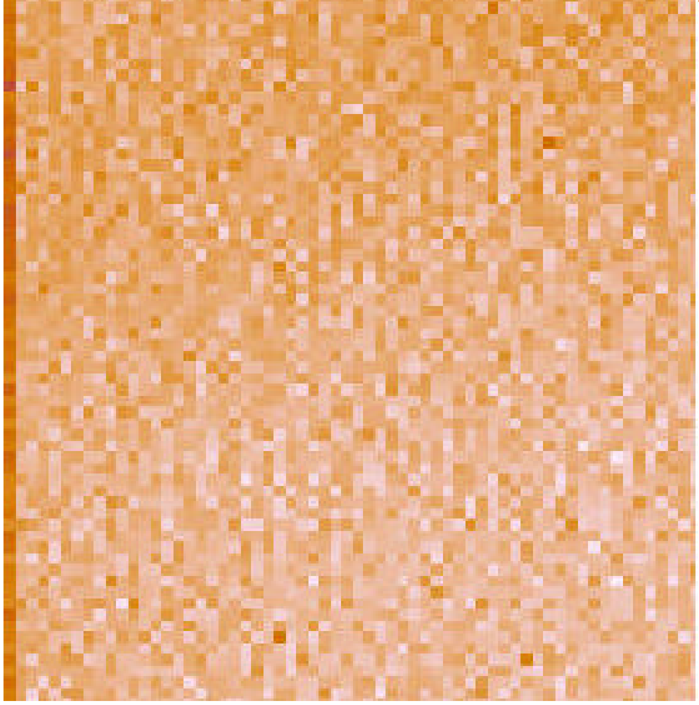
Defect Results from Exposures

	# defect (> 6 e^-) 800,000 pixels	# defect (>20e^-) 800,000 pixels
Prior to exposure	125	24
Following 2×10^9 n/cm^2 (source)	916	160
Additional 2×10^9 n/cm^2 (reactor)	5476	442
Additional 1.2×10^9 n/cm^2 (reactor)	7036	298*

* this drop in defect count is not understood,
but may be related to thermal cycling.

Image of damaged
sites ⇒





⇐ Image of
damaged sites
after flushing

Signal Loss Results from Exposures

	$\sim 2 \times 10^9$ n/cm^2	$\sim 5.2 \times 10^9$ n/cm^2
T = 185K, cluster sum no flushing light	4.05%	29.1%
T = 185K, cluster sum with flushing light	1.5%	18.0% *
T = 178K		11.0% *

Note (*) - flush is only partially effective in test set-up due
to required delay between flush and readout (1 second)
In LC detector – much reduced loss

Issues needing further and refined study:

Dependence of physics performance on vertex detector parameters

Parameters:

- Inner radius
- Outer radius
- Number of barrels
- Angular coverage
- Hit Resolution
  - (pixel size)
- Background pile-up
  - (layer dependent; related to B)

Study impact of each of these on physics perform.

Performance measures:

- Impact parameter resolutions
- Tagging efficiencies and purities
  - b quarks
  - charm
  - taus
- Specific channels studies
  - eg. Higgs -> c c-bar

We still need to incorporate vertex recon. (ZVTOP3)into LCD simulation.
(we should have this soon)

Radiation backgrounds and design advances to enhance radiation tolerance.

Conclusions

Vertex Detection with CCDs at the Linear Collider is quite mature (thanks to SLD), but the unique physics opportunities at the next Linear Collider require further advances.

rad-hardening of CCDs, faster CCDs......

Radiation hardness studies of CCDs have started and show promise to provide techniques to deal with the more hostile environment of the higher energy Linear Collider.

flushing techniques, etc.

➔ but more work is needed

Several simulation physics performance studies are underway, and we should these soon to clarify/justify the requirements for the vertex detector.