CCD Vertex Detector

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Sitges, Spain
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Physics of Linear Collider demands the best possible vertex detector performance

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

CCDs offer the most attractive avenue for achieving this performance

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

VXD1 (1991)	prototype
VXD2 (1992-95)	compete detector
VXD3 (1996-)	upgrade

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

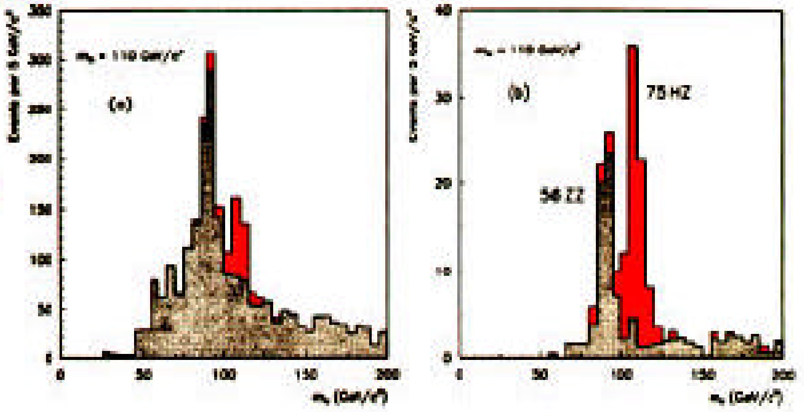
($\sim\frac{1}{5}$ NLC yr)

1. $\equiv 4$ jets w/ $M_{jet} < 45$ GeV ($e^+e^- \not\to q\bar{q}$)
2. $E_{tot} > 0.7\sqrt{s}$ ($\cancel{t}\nu$)
3. χ^2_{WW} 75 (fit) (WW)
4. $M_{ij} \sim M_Z$ (80-125 GeV)

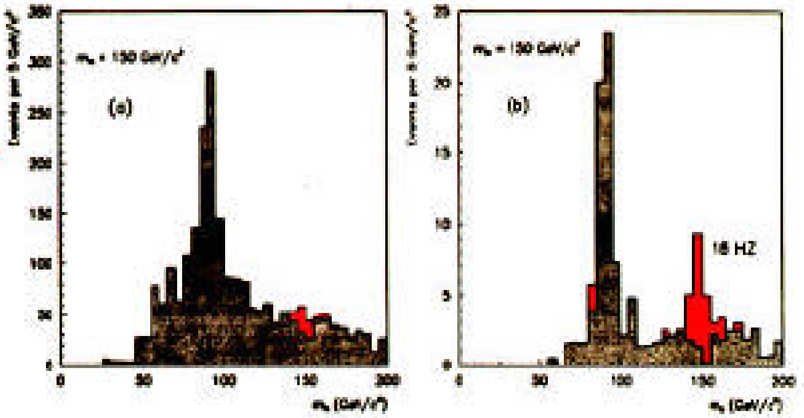
no b tag

$b\bar{b}$ tag

M_H = 110 GeV/c^2 ↳



M_H = 150 GeV/c^2 ↳



Janot

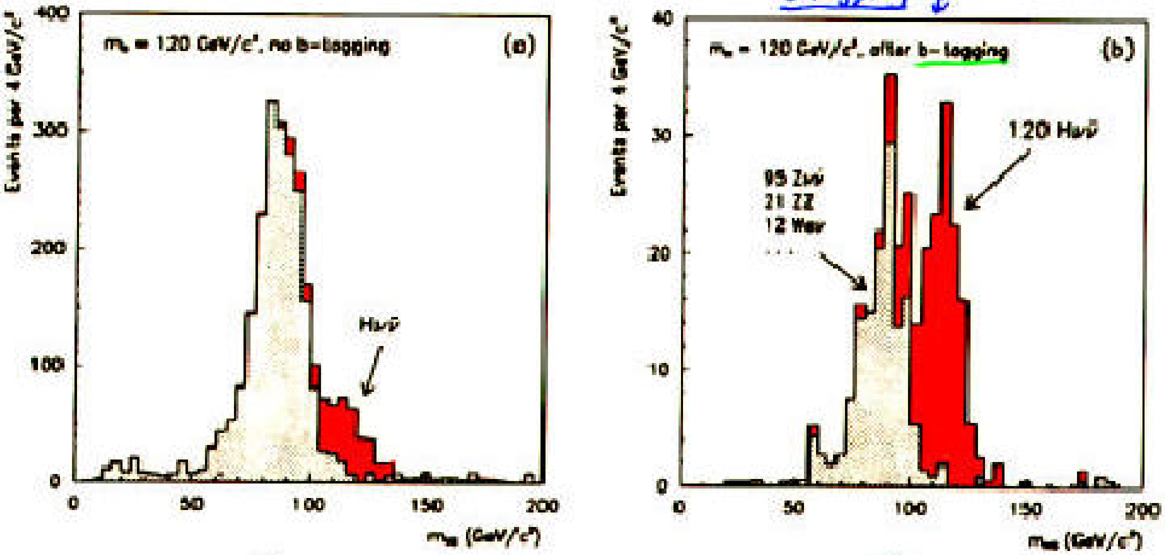
$e^+e^- \to H\nu\bar{\nu}$ @ $\sqrt{s} = 500$ GeV/c² w/ 10 fb⁻¹ (~ $\frac{1}{5}$ NLC year)

1. $E_{miss} > \sqrt{s}/2$
2. $\not{P}_T > 40$ GeV/c
3. MM > 200 GeV/c²
4. $\theta_{prod} > 25°$
5. $\theta_{acopl.} < 150°$
6. veto isolated leptons

hermeticity

diject mass resolution

b tagging ?



M_{vis} M_{vis}

Janot

Advantages Offered by CCDs

- Intrinsically 3-dimensional

- High granularity
  - $20 \times 20 \times 20\ \mu m^3$ pixels
  - superb spatial resolution
    - $< 5\ \mu m$ achieved

- Thin
  - 0.4% X_0 presently
  - low multiple scattering

- Large detectors
  - $80 \times 16\ mm^2$ in VXD3
  - facilitates ease of geometry

- SLD Performance has been exceptional
  - CCDs are well matched to the 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 outer detector
  compact, conventional, ??

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

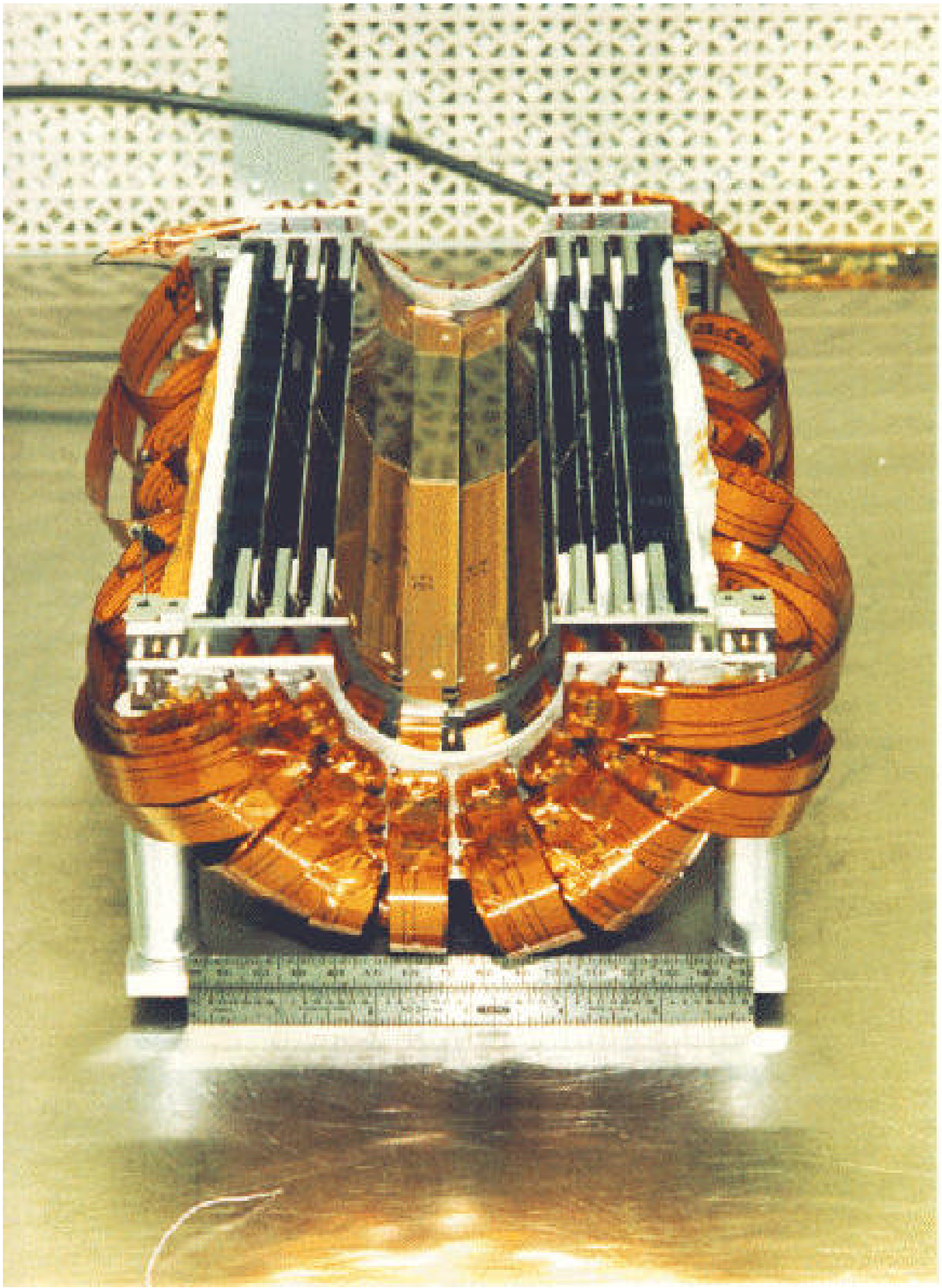
⇒ radiation immunity
* design shielding to protect CCDs
* improve CCD tolerance

CCDs current state-of-the-art

- SLD with 307,000,000 pixels
- 10 MHz readout of CCD (5 MHz operational)
- < 5 µm point resolution
- exceptional efficiency and purity

$$s_{rf}^{IP} = 9mm \oplus \frac{33mm}{p \sin^{3/2} q}$$

Improvements are desirable (if not required)
for the Linear Collider



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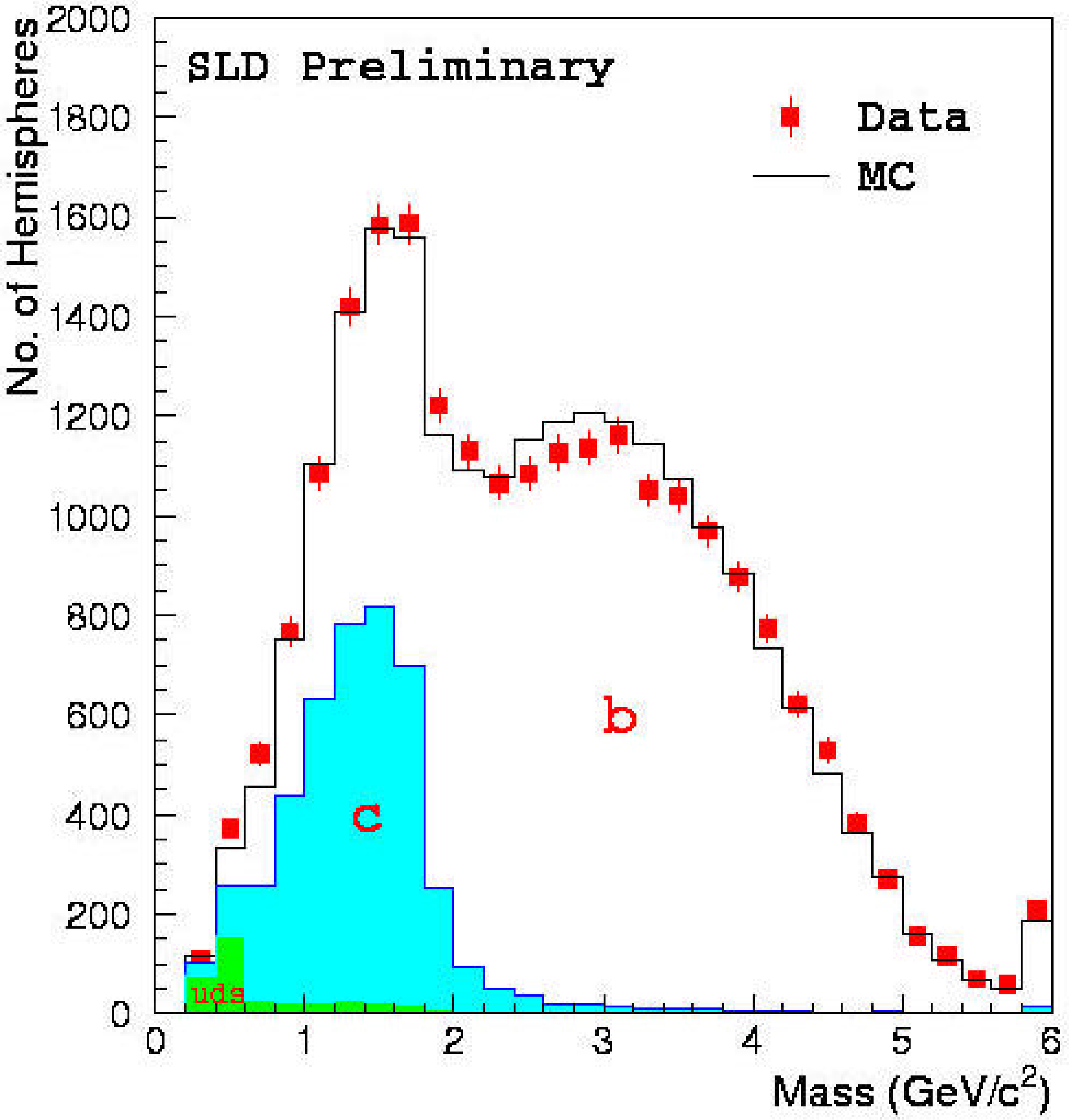
SLD Preliminary
Data
MC
No. of Hemispheres
Mass (GeV/c^2)
b
c
uds
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
1
2
3
4
5
6

Vertex Detector Design

for the future Linear Collider

- Maximum Precision ($< 5\ \mu m$)
- Minimal Layer Thickness
  $(1.2\%\ X_0 \rightarrow 0.4\%\ X_0 \rightarrow 0.12\%\ X_0)$
  SLD-VXD2 SLD-VXD3 Linear Collider
- Minimal Layer 1 Radius (28 → 12 mm)
- 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)

Radiation Hardness Tests of CCDs

Nick Sinev
Univ. of Oregon

Background estimates have varied from 10^7 n/cm^2/year
to 10^{11} n/cm^2/year
NOW- best est. 2 x 10^9 n/cm^2/year (Maruyama)

Expected tolerance for CCDs
in the range of 10^9 (C. Damerell)
but more investigation is needed

In addition, can one develop procedures to increase tolerance

Radiation damage studies are called for
- improve understanding of issues and sensitivity
- improve radiation hardness
  - flushing techniques
  - supplementary channels

Existing data on radiation hardness of CCDs

limited

S. Watts et al, 1995

at 3.6×10^{9} (10 MeV p)/cm^{2} CTI increases to 10^{-3}.

this corresponds to about 3×10^{10} n/cm^{2}

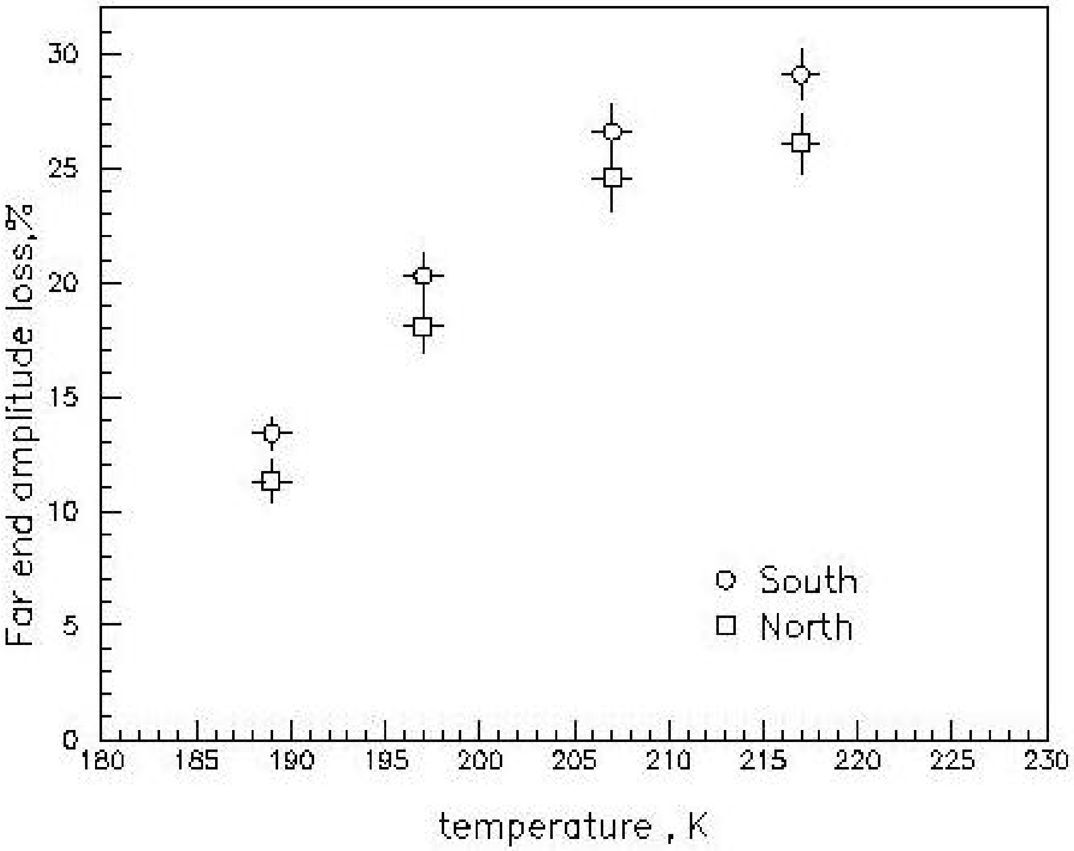
SLD Experience

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 trying to operate the detector at an elevated temperature (≈220 K).

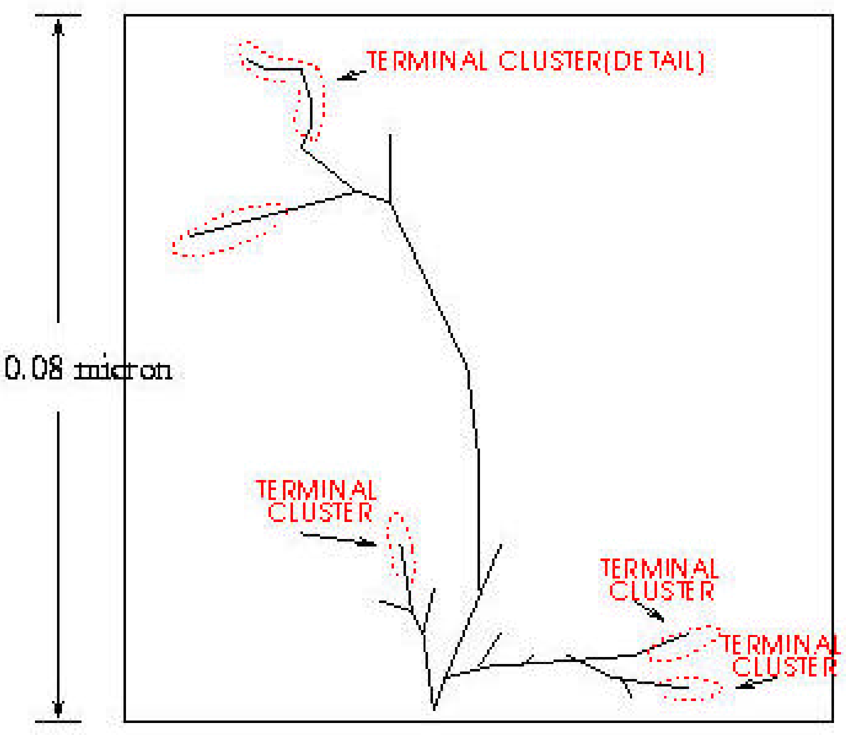
Reducing the temperature to 190 K ameliorated the damage



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

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.



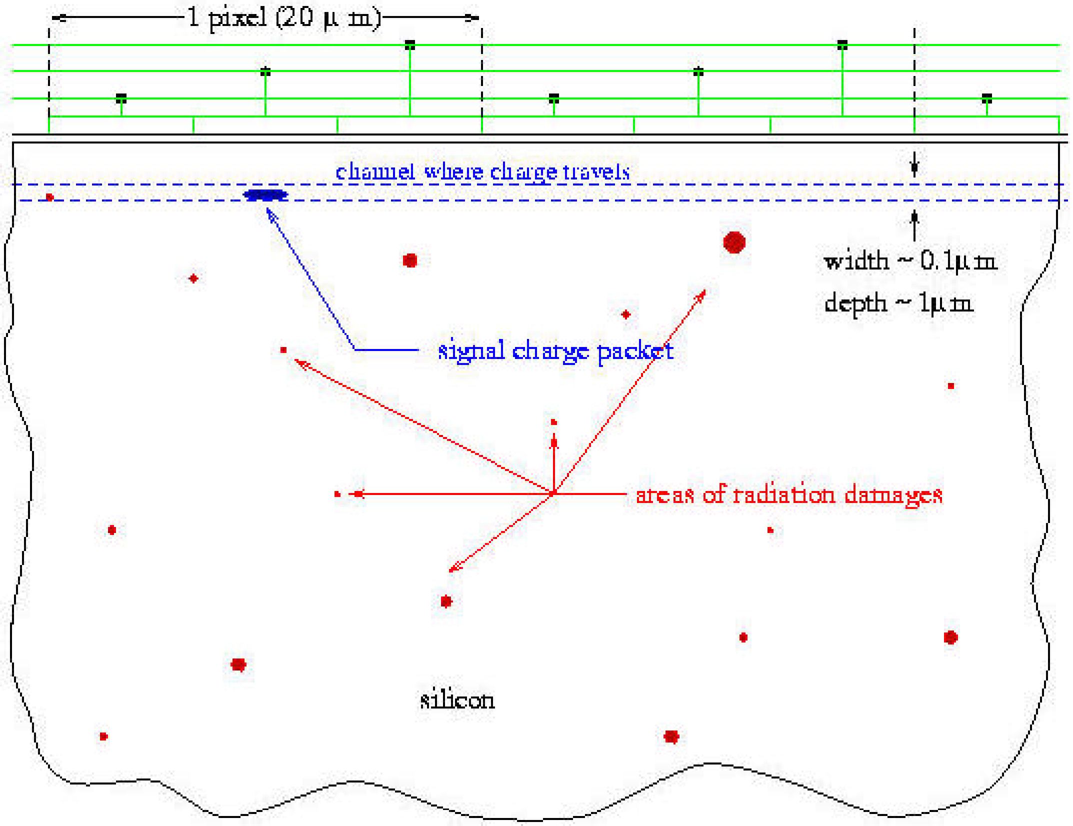
Example of simulated tracks of knock-out silicon atoms from a primary knock-out energy of 40 keV. (V.A.J.Van Lint, NIM A253, 453 (1987).)

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

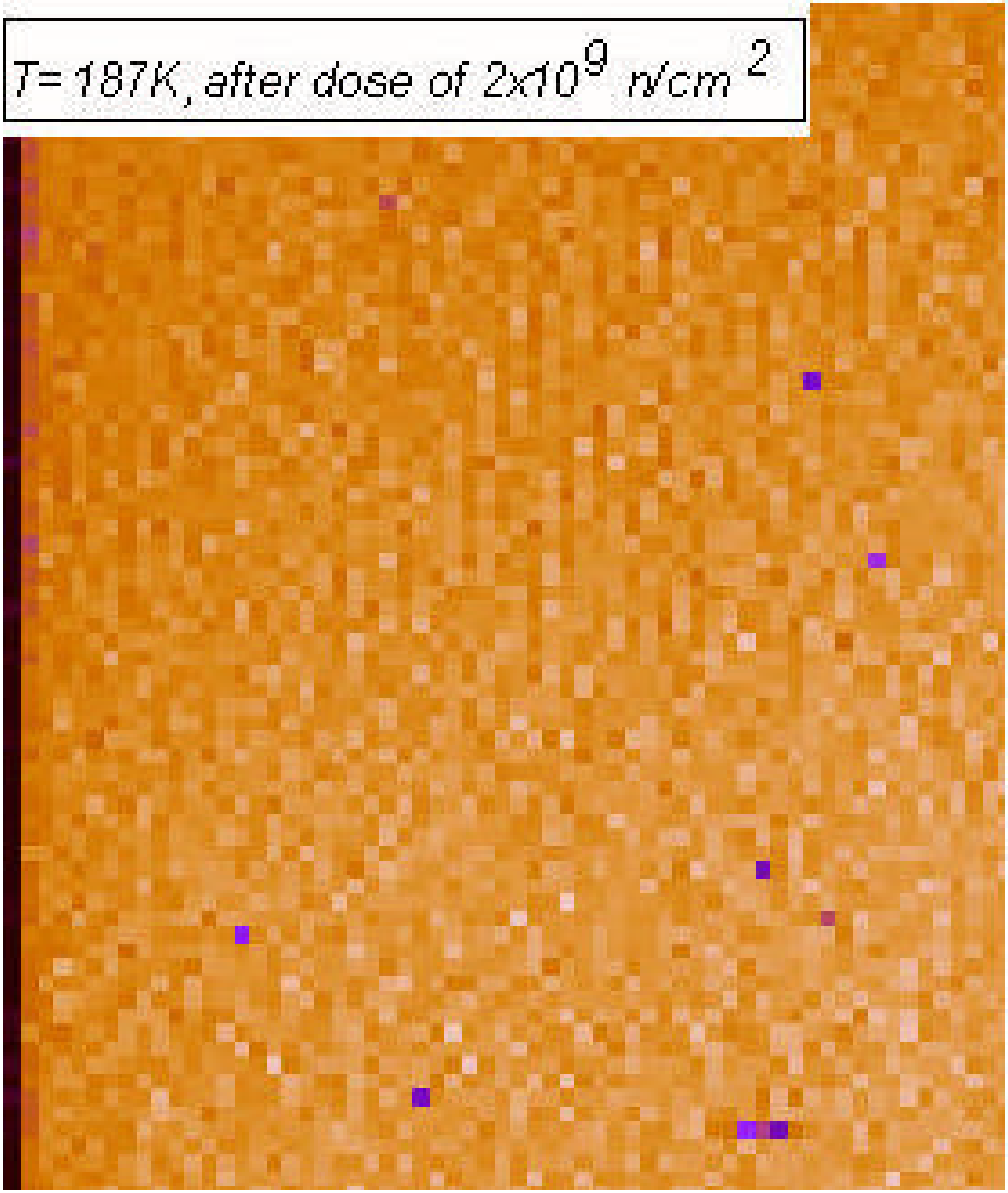
(spare SLD VXD3 CCD)

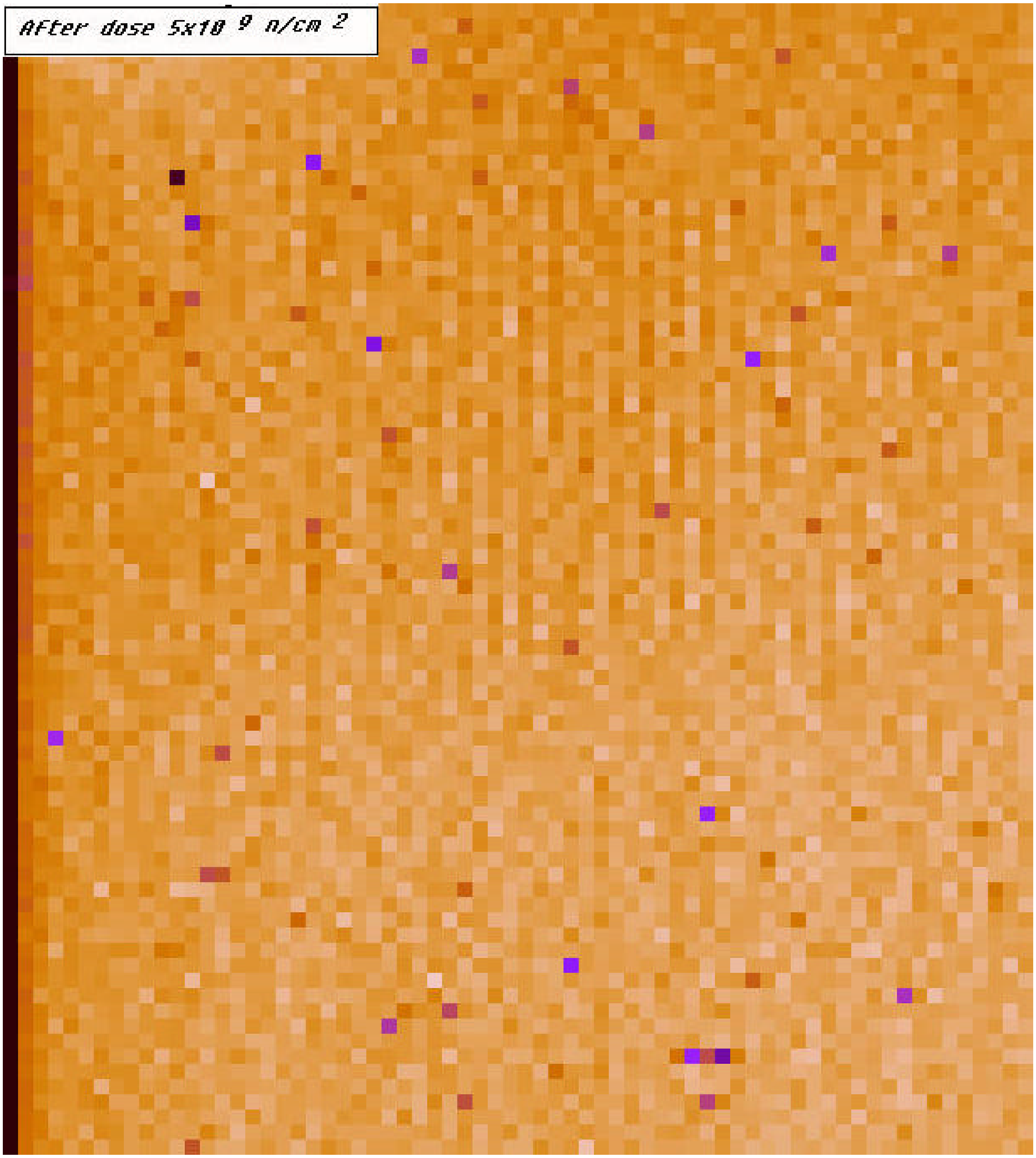
Nov 98	~ 2×10^9 n/cm^2 Pu(Be) $\langle E_n \rangle \approx 4$ MeV	room temperature
Dec98 -Jan 99	Annealing study	100° C for 35 days
Mar 99	~ 3×10^9 n/cm^2 reactor* neutrons $\langle E_n \rangle \approx 1$ MeV (~1×10^9 n/cm^2 lower energy)	room temperature
Apr 99	~ 1.5×10^9 n/cm^2 reactor* neutrons $\langle E_n \rangle \approx 1$ MeV (~1×10^9 n/cm^2 lower energy)	dry ice cooled (~190K)

Total exposure ~ 6.5×10^9 n/cm^2

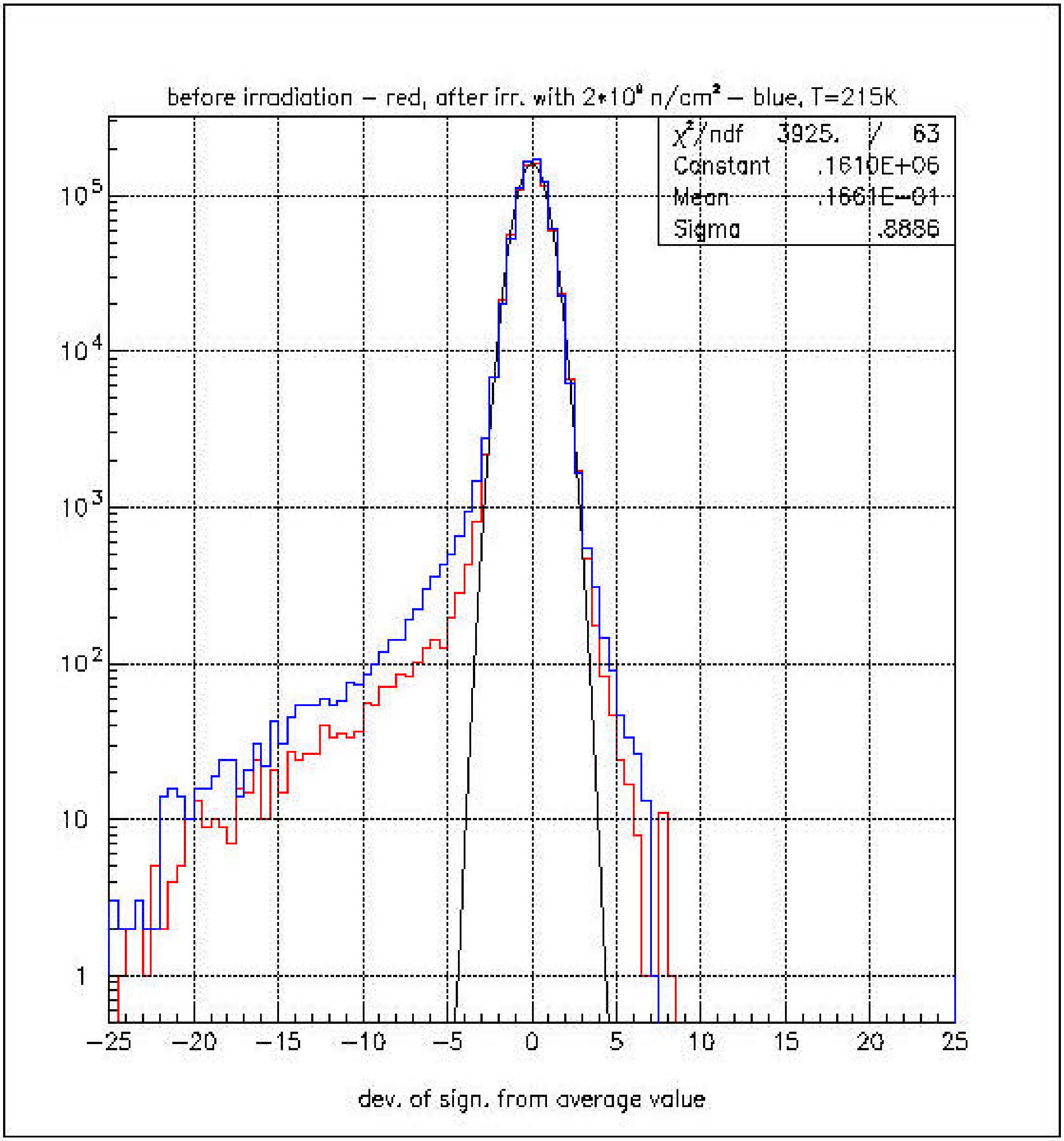
mix of source and reactor

* UC Davis (G. Grim et al)


T= 187K, after dose of $2x10^{9}$ n/cm^{2}



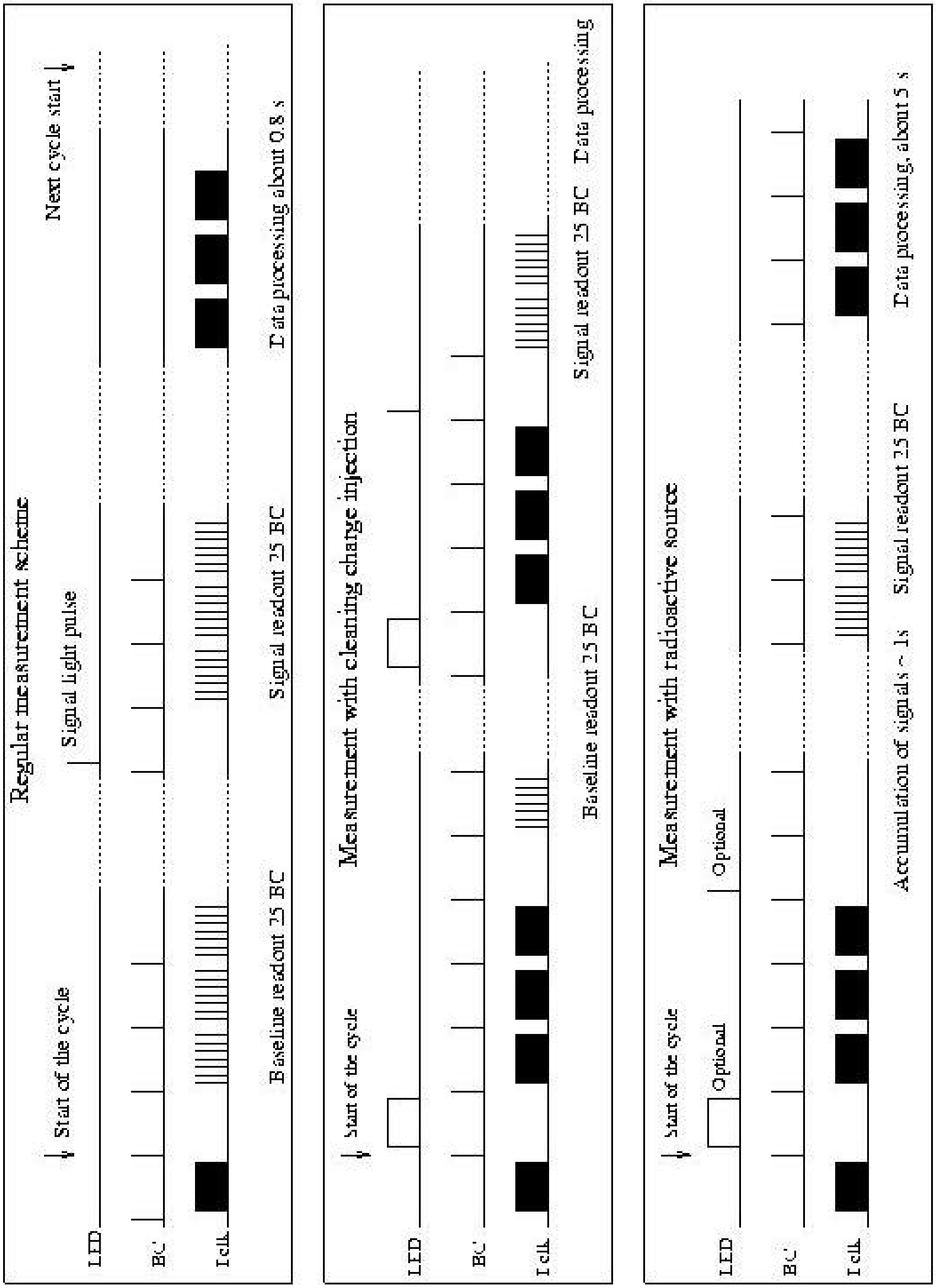
After dose $5x10^{9}$ n/cm^{2}

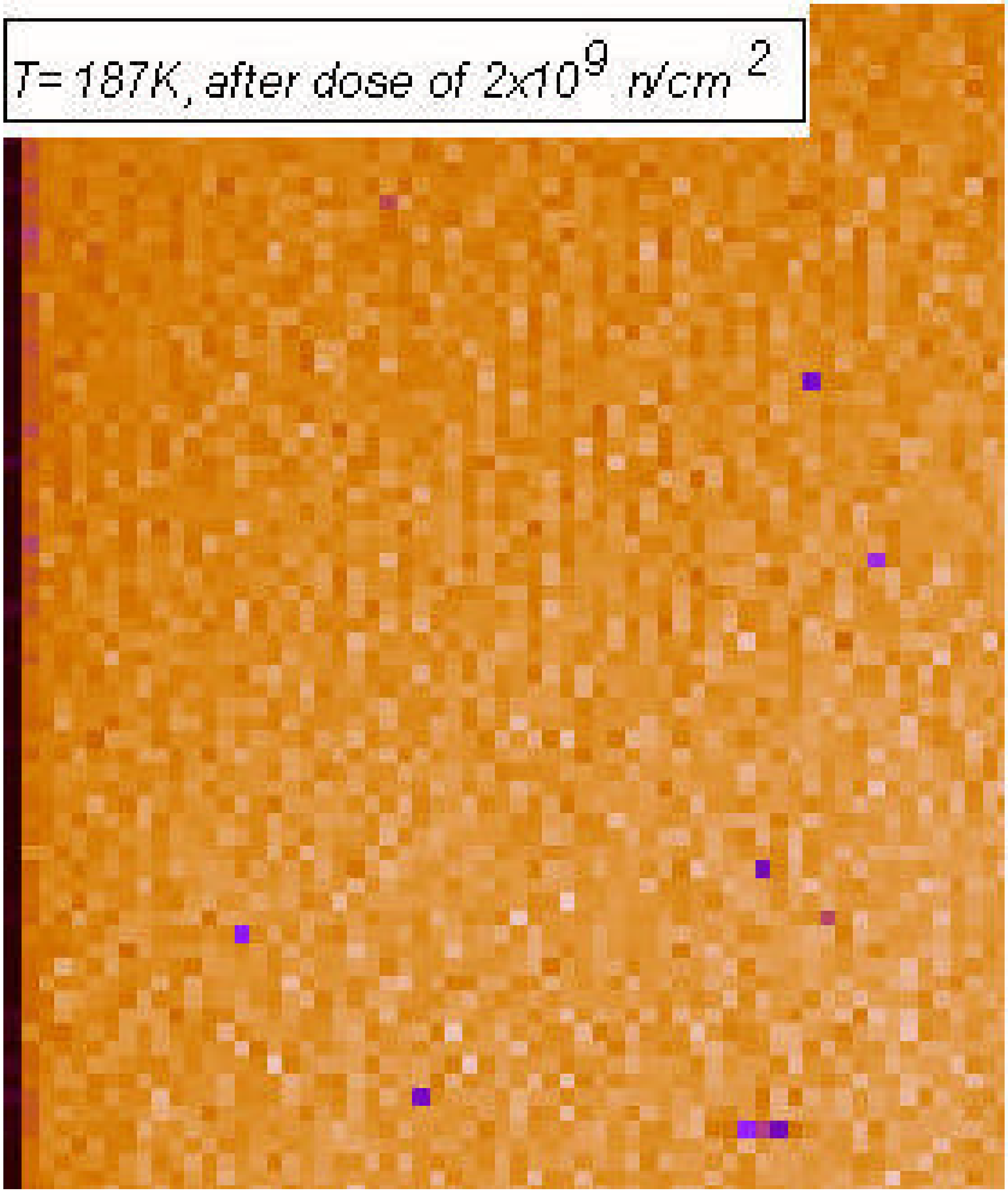

before irradiation – red, after irr. with 2*10⁹ n/cm² – blue, T=215K
χ^2/ndf 3925. / 63
Constant .1610E+06
Mean .1661E–01
Sigma .8886
10⁵
10⁴
10³
10²
10
1
–25
–20
–15
–10
–5
0
5
10
15
20
25
dev. of sign. from average value

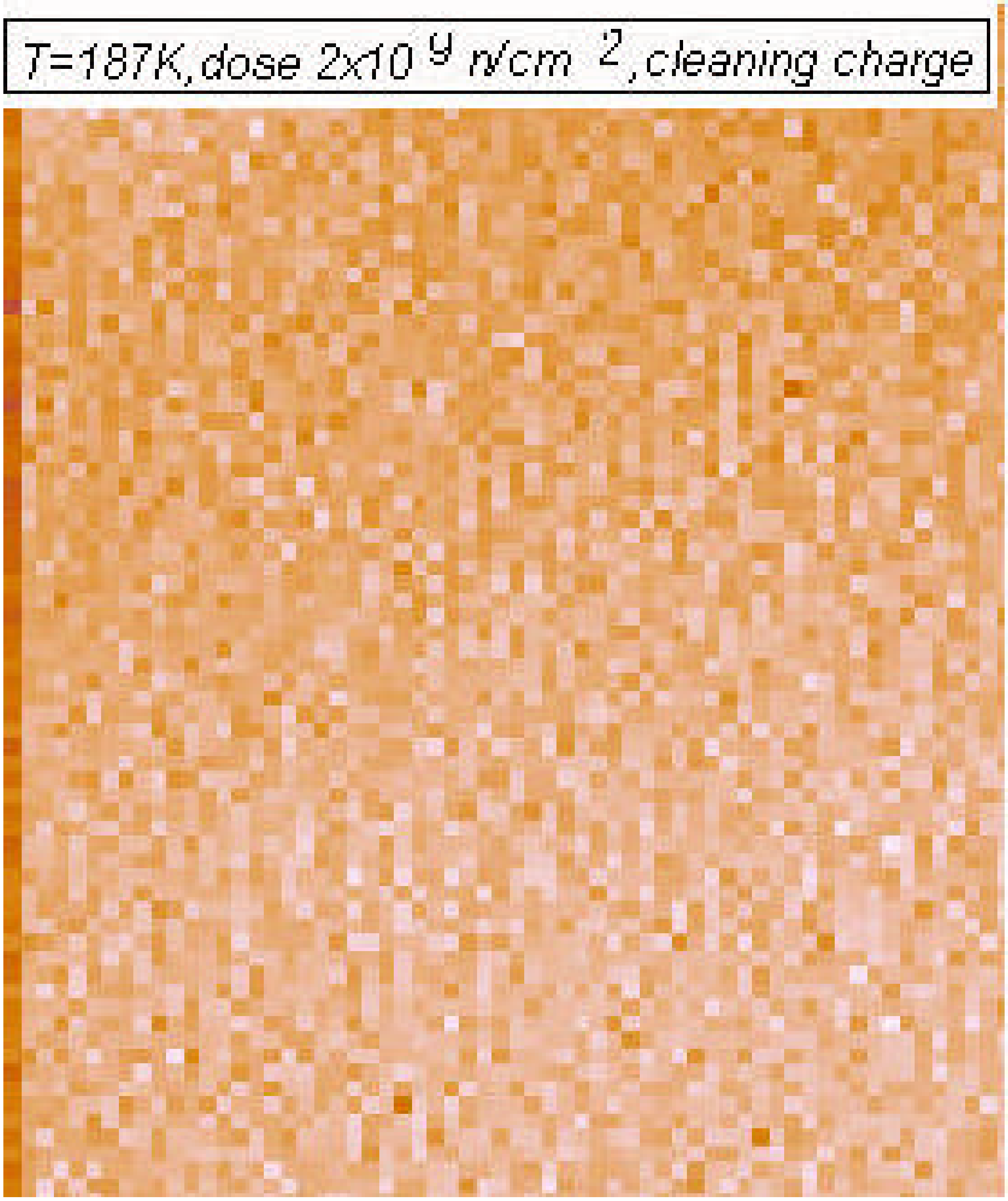
Defect Results from Exposures

	# defect (> 6 e^-) 800,000 pixels	# defect (>20e^-) 800,000 pixels
Prior to exposure	125	24
Nov 98 exposure ~ 2×10^9 n/cm^2 source	916	160
Mar 99 exposure $\times 10^9$ n/cm^2 reactor	5476	442*
Apr 99 exposure + ~ 1.5×10^9 n/cm^2 reactor	7036	298*

* this surprising decrease
is not understood


Regular measurement scheme
Start of the cycle
Signal light pulse
Next cycle start
LED
BC
I clk
Baseline readout 25 BC
Signal readout 25 BC
Data processing about 0.8 s
Measurement with cleaning charge injection
Start of the cycle
LED
BC
I clk
Baseline readout 25 BC
Signal readout 25 BC
Data processing
Measurement with radioactive source
Start of the cycle
Optional
Optional
LED
BC
I clk
Accumulation of signals ~ 1s
Signal readout 25 BC
Data processing, about 5 s


T=187K, after dose of 2x10^9 n/cm^2



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

Signal Loss Results from Exposures

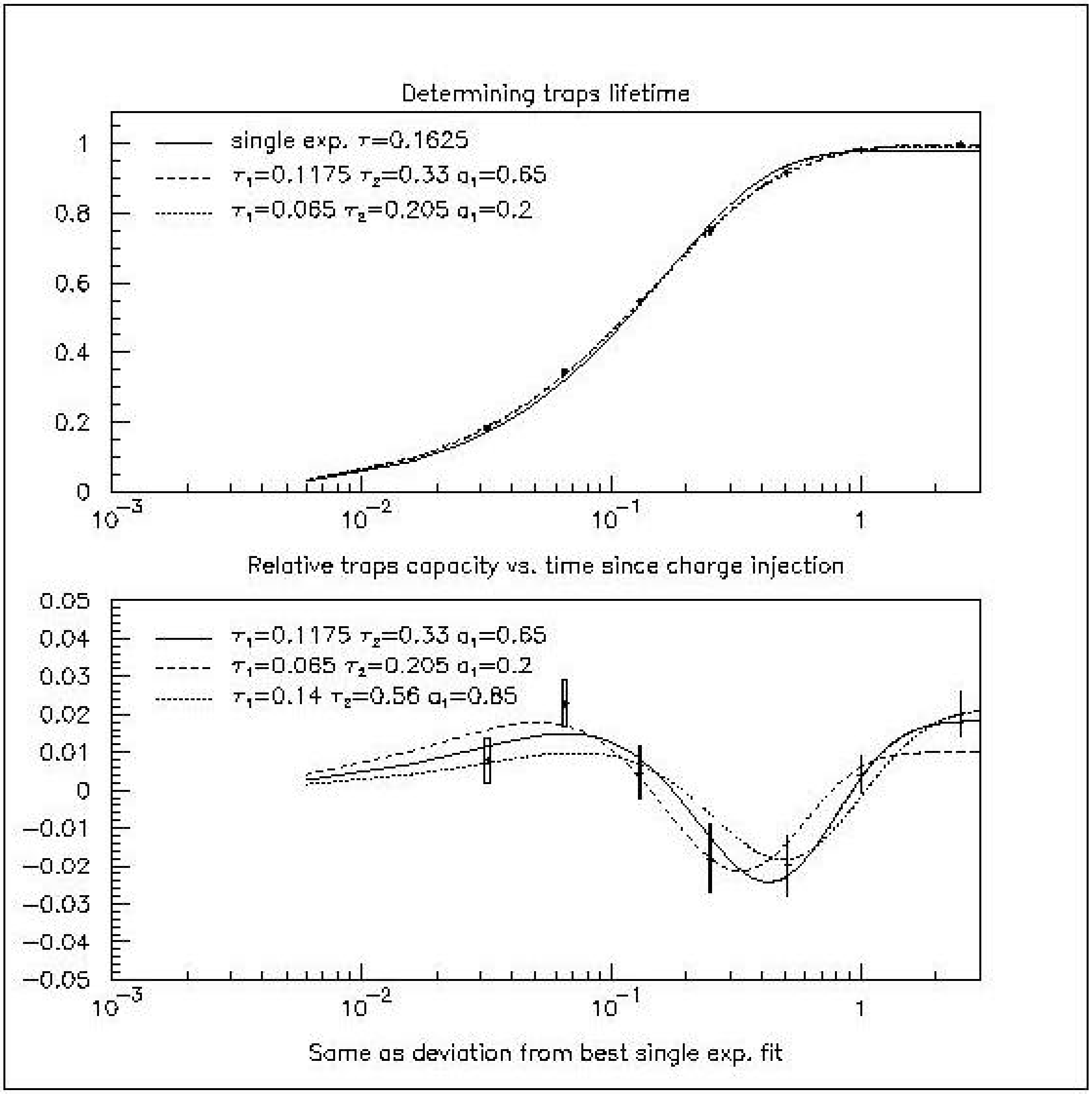
	~ 2×10^9 n/cm^2	~ 6.5×10^9 n/cm^2
T = 185K, cluster sum no flushing light	4.05%	29.1%
T = 185K, cluster sum with flushing light	1.5%	18.0% *
T = 178K		11.0% *

Note (*) - flush is only partially effective due to required delay between flush and readout (1 second)

In LC detector – much reduced loss

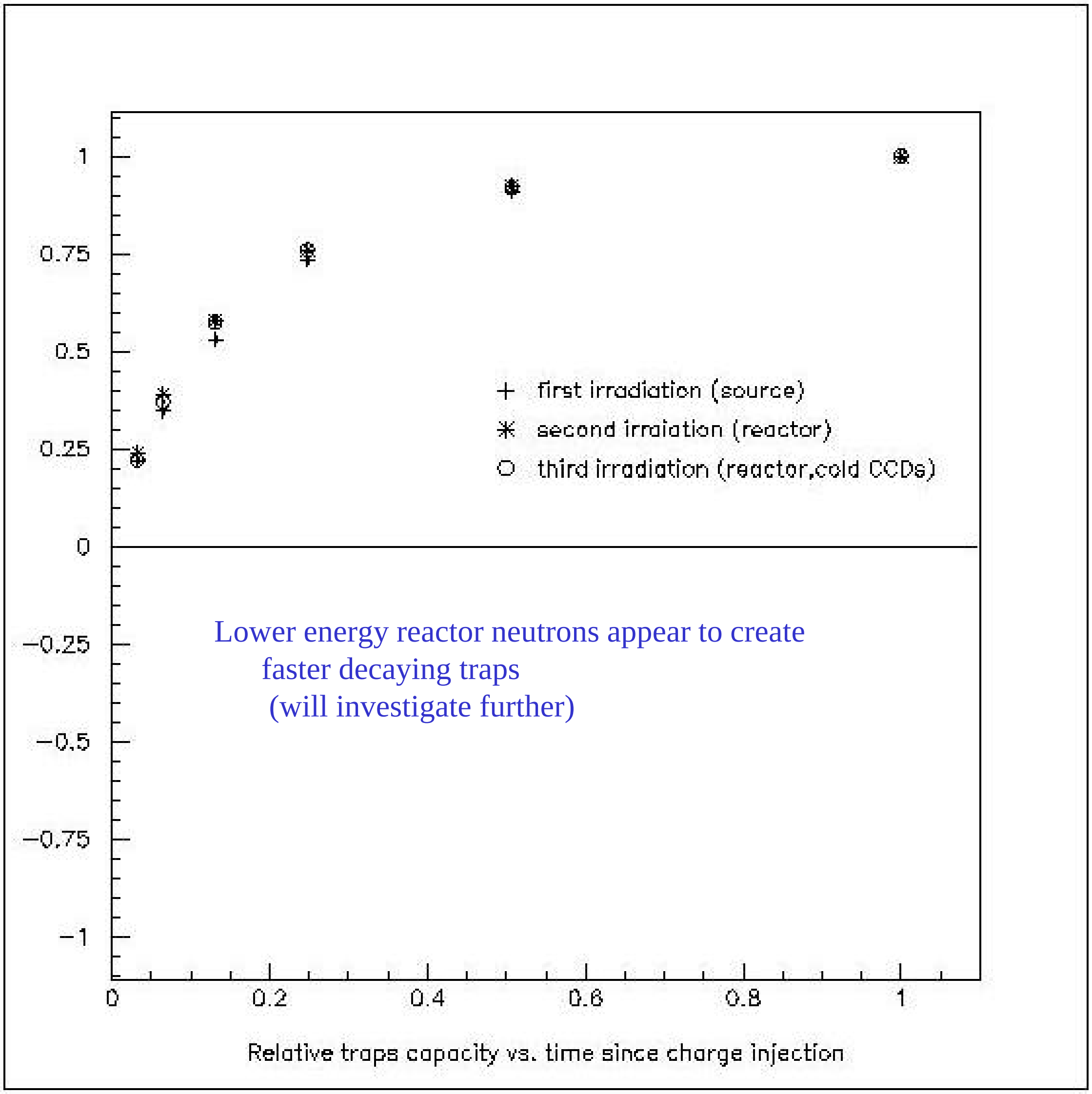
-will estimate in future tests

$$t = \frac{e^{(E_c - E_{tr})/kT}}{s_N c_N n_N N_c}$$

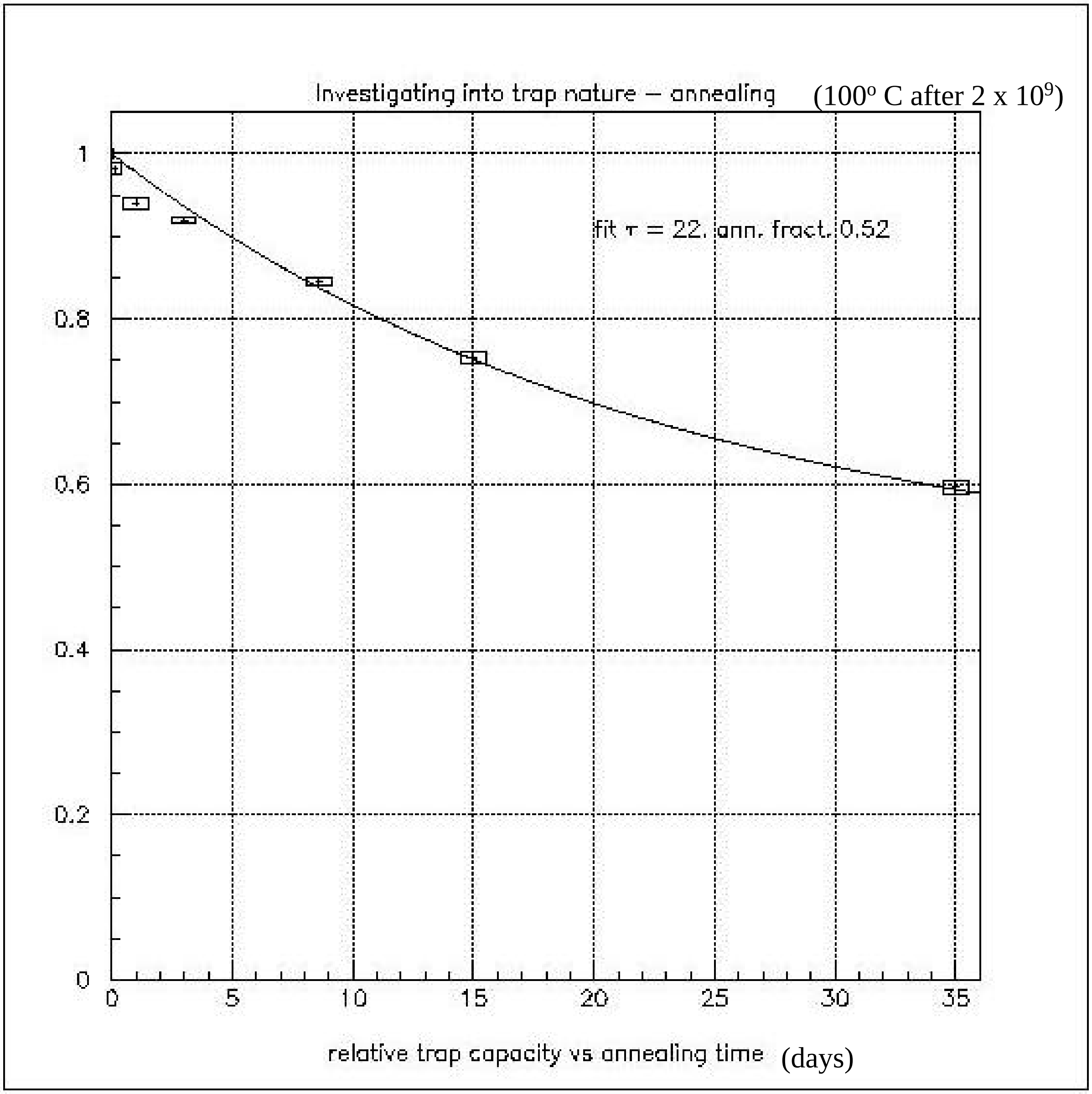

Determining traps lifetime

Relative traps capacity vs. time since charge injection

Same as deviation from best single exp. fit



Lower energy reactor neutrons appear to create
faster decaying traps
(will investigate further)


Investigating into trap nature – annealing (100° C after 2 x 10^9)
fit τ = 22. ann. fract. 0.52
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
relative trap capacity vs annealing time (days)

Identifying the Nature of the Radiation Damages

By measuring the trap lifetimes at two different temperatures, T1 and T2, the energy levels can be derived for the simple relationship:

$$\ln\left(\tau 1/\tau 2\right) = \frac{(Ec-Etr)}{K}\left(\frac{T2 - T1}{T2 * T1}\right)$$

From this it is easy to find Ec-Etr, can be compared to energy levels of known defects.

Defect identity	Energy level	Defect type
VO	Ec - 0.17	acceptor
V2O	Ec - 0.50	acceptor
V2	Ec - 0.23 Ec - 0.42 Ev + 0.25	acceptor acceptor donor
VP	Ec - 0.45	acceptor
CC	Ec - 0.17	acceptor
CO	Ev + 0.36	donor

Conclusions

Vertex Detection is quite a mature technique, but the unique physics opportunities afforded by the next Linear Collider could benefit from further advances.

CCDs offer a proven technology with the best possible performance demonstrated by SLD at SLC.

Radiation hardness studies of CCDs are demonstrating advances in our ability to deal with the environment of the higher energy Linear Collider.

Radiation induced defects can be amelioriated with flushing techniques, where traps are filled, allowing signal charges to pass undisturbed.