Radiation Damage in the CDF RunII Silicon…
Revisited

Steven Worm
CERN / RAL

(with lots of help from the CDF Silicon Group)

Outline

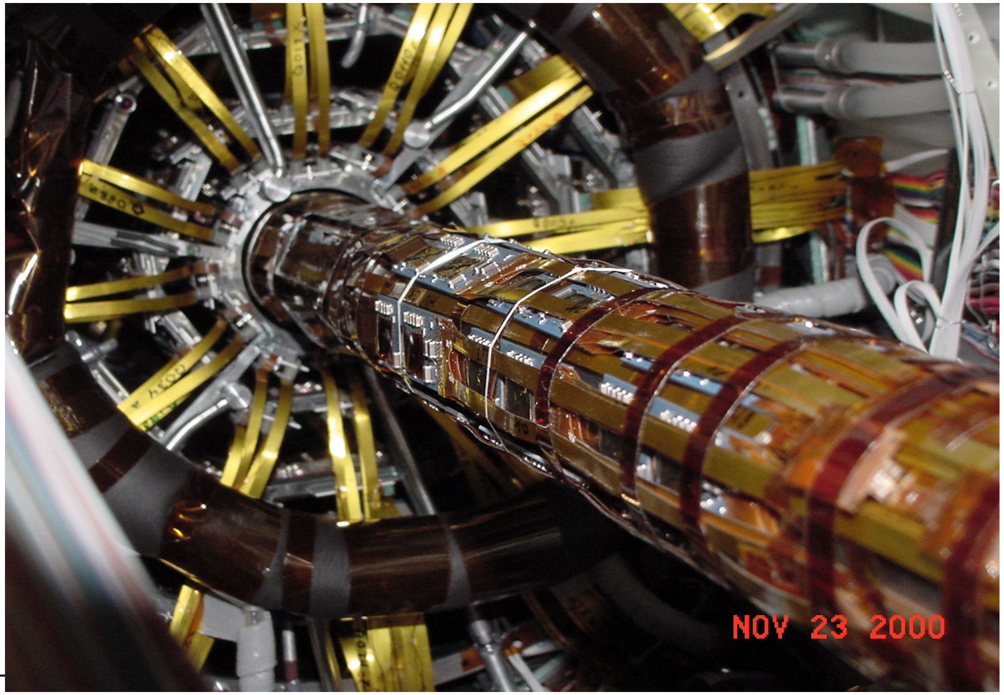
Some early issues, concerns

Radiation damage basics

Measuring the radiation field

Lifetime of the Run IIa silicon

Conclusions



Worries in the 15-year Lifecycle of CDF Si

[dark ages]

Read-out Chip yield

SVX Jumper problems

Scratches on the sensors

[birth]

ISL cooling blockage

L00 noise problems

Wirebond resonance issues

Catastrophic beam losses

Unrecoverable readout chip problems

[middle age]

Endless battle to recover bits not working

More cooling problems

[old age]

Radiation damage

Comment 1: initially we had a lot more important things to worry about (operations)

Comment 2: that CDF had to worry about radiation damage is testament to the hard work of many people in keeping it running

Comment 3: early radiation monitoring provided "sanity check" and ammunition for upgrade proposal

Many Thanks… and References

CDF Silicon SPL's and others: Benedetto di Ruzza, Michelle Stancari, Oscar Gonzalez Lopez, Mark Mattson, Roberto Martinez Ballarin

Vertex 2011: Michelle Stancari

http://indico.cern.ch/conferenceDisplay.py?confId=104062

TIPP 2011 Chicago : Benedetto Di Ruzza

http://indico.cern.ch/getFile.py/access?contribId=148&sessionId=22&resId=1&materialId=slides&confId=102998

Fermilab User Meeting: Miguel Mondragon

https://indico.fnal.gov/getFile.py/access?contribId=30&sessionId=5&resId=0&materialId=slides&confId=4444

4th National Course on "Detectors and Electronics for High Energy Physics, Astrophysics, Space and Medical Applications" (Padua, Italy) Benedetto Di Ruzza

http://agenda.infn.it/materialDisplay.py?contribId=12&materialId=slides&confId=3245

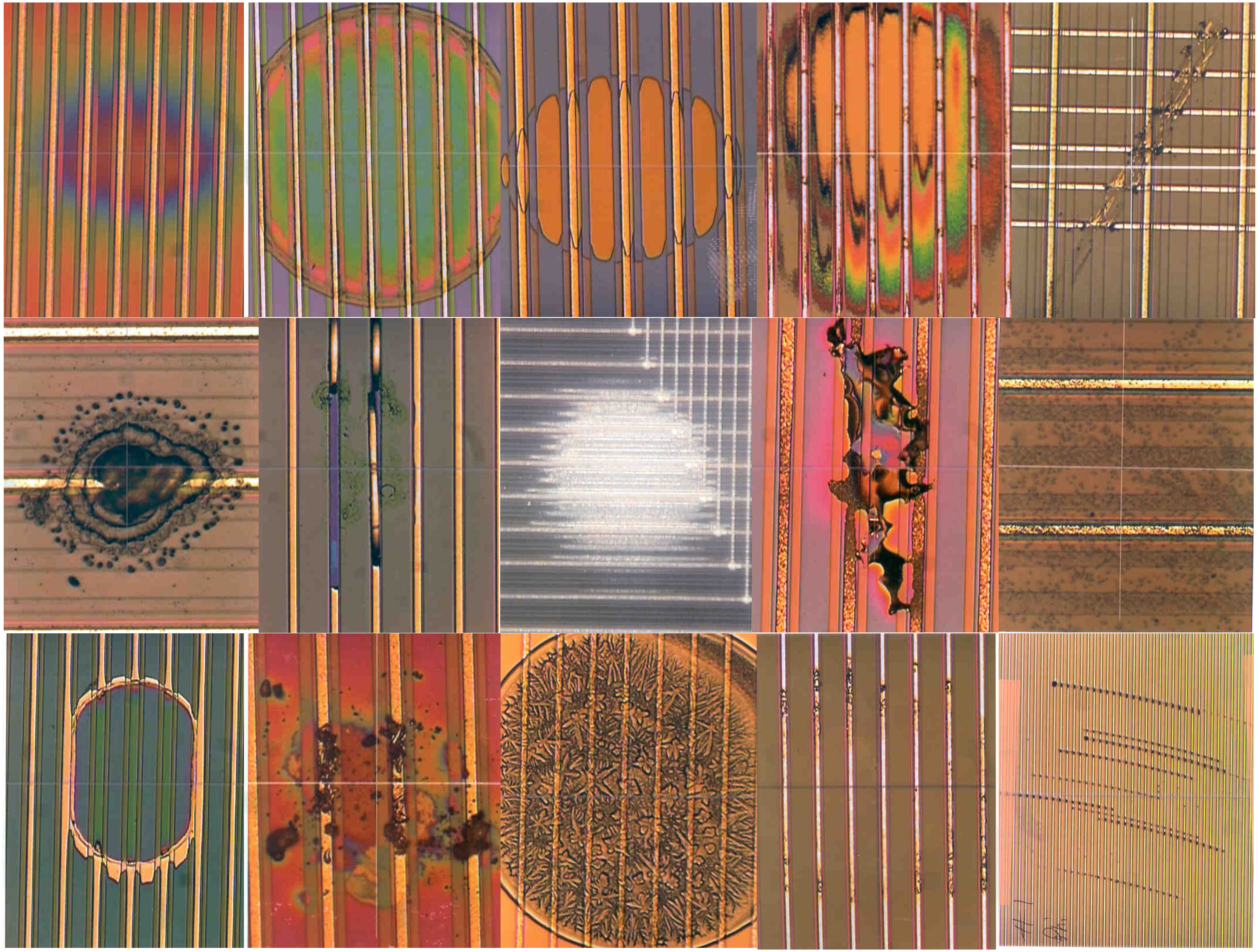
Robero Ballarin thesis (CIEMAT Madrid, Oscar Gonzalez Lopez's student)

http://lss.fnal.gov/archive/thesis/fermilab-thesis-2011-28.shtml

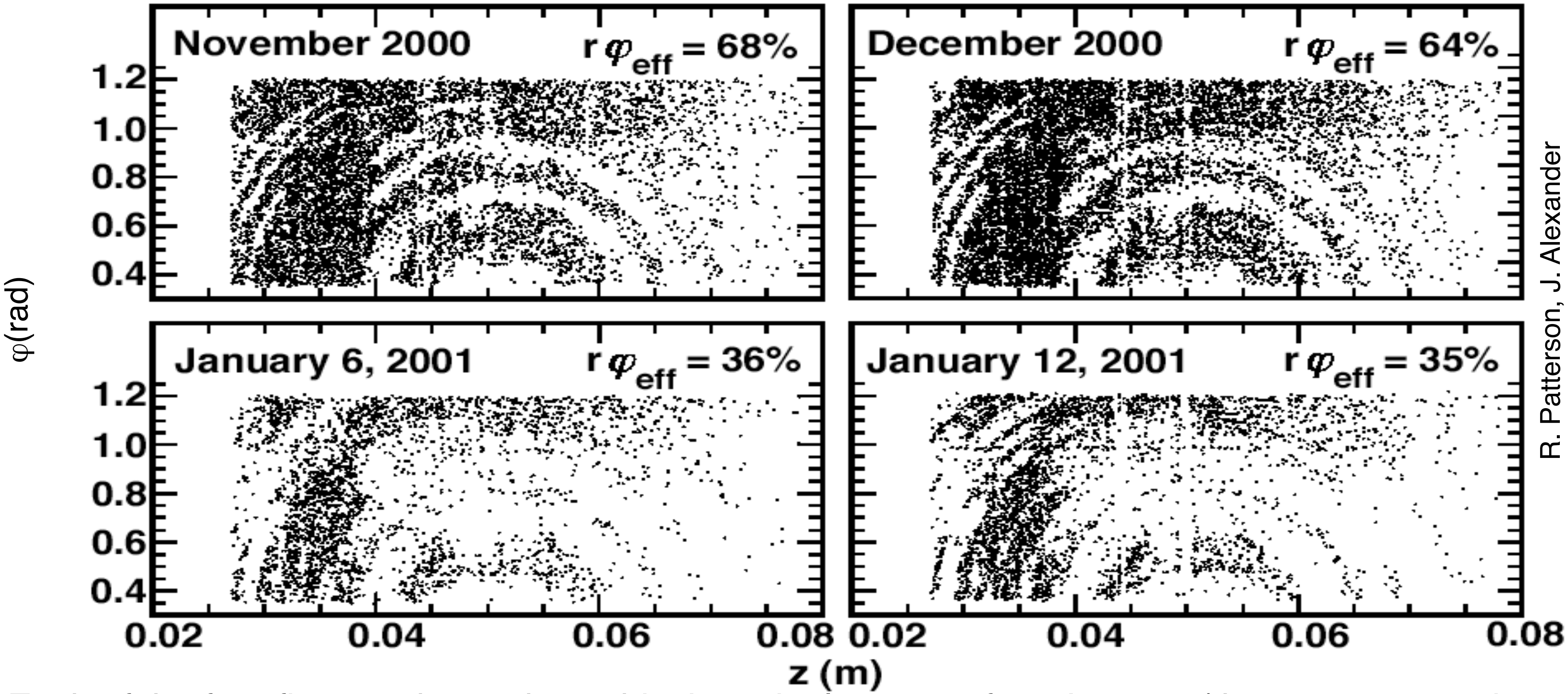
Gratuitous old photo, circa 2001

Thanks too to those from the "dark ages"…

Early worries: Process Defects and Scratches



CLEO III Layer 1 Silicon Sensor



Each of the four figures above shows hits in a single sensor from Layer 1 (the same sensor in each case) over the course of a few months.

The overall left-right variation of intensity is due to the angular distribution of Bhabha tracks from which the plots are made, and the overall number of hits in each plot is simply determined by the length of the run from which the plot was made. Vertical and horizontal stripes indicate specific problems with preamp channels (vertical = z-strips = p-side, horizontal = rphi-strips = n-side).

Sensor Comparison

L00

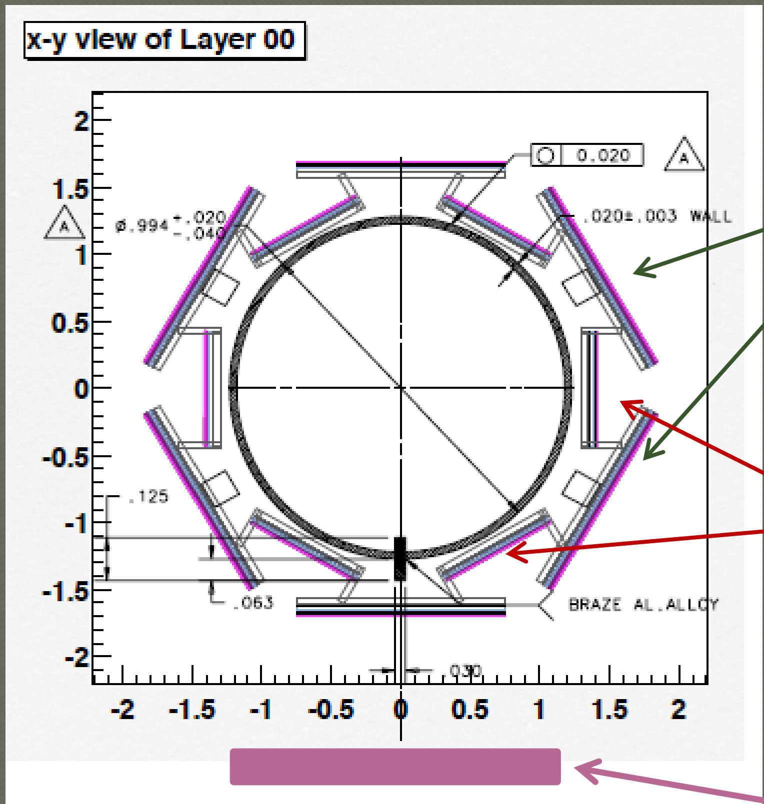
- p+ strips on n bulk
  single-sided
- <100>-orientation
- Sensor breakdown >600 V
  Power supplies <500 V
- Actively cooled sensors
  (-12 °C)
- Hybrids outside tracking volume
- Read out all channels each event

SVX

- p+ strips on n bulk
  double-sided
- <111>-orientation
- Sensor breakdown
  170-200 V
- Not actively cooled (~0 °C)
- Hybrids attached to sensors
- Displaced track trigger requires nearest neighbor readout

L00 designed to outlast SVX-L0 however bulk properties are the same!

L00 geometry

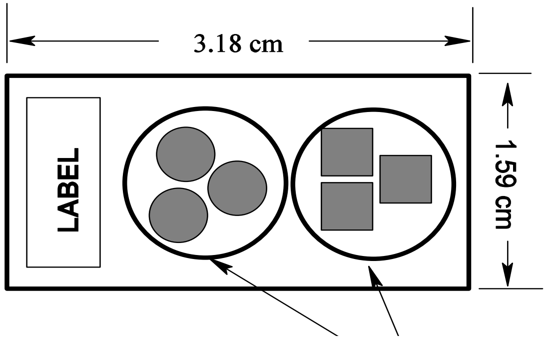


"Wides" at r=1.62 cm
made by Hamamatsu

"Narrows" at r=1.35 cm
made by SGS Thomsen
** 2 of 12 are special oxygenated sensors from Micron for R&D

SVX-L0 r=2.54 cm

Measuring Radiation: Tracking Volume TLDs

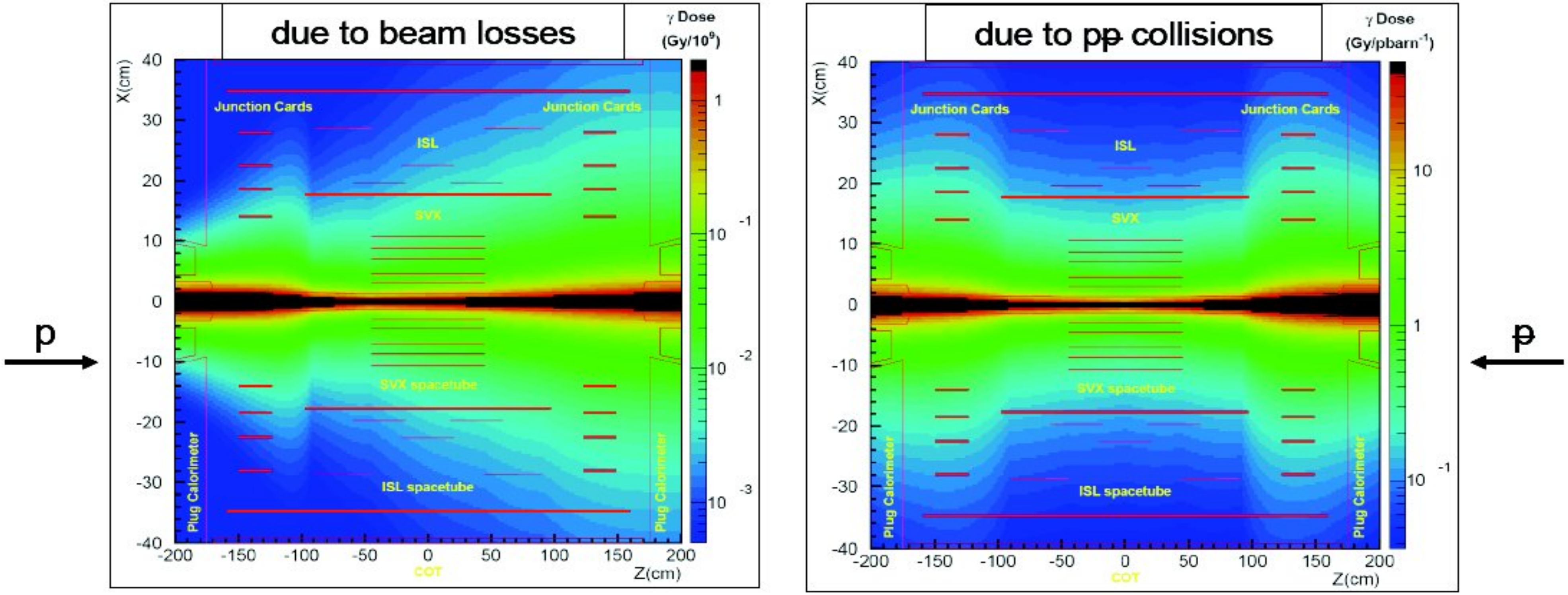


TLDs with ^{7}Li, ^{6}Li
Sensitive to γ, n

- TLD placement
  - TLD holders attached to kapton film and pulled into place like a 'clothesline'
  - Kapton leads fed through cables for silicon and drift chamber
  - Finding the ends can be difficult!

Radiation Field in CDF Tracker

- Measured using more than 1000 thermo-luminescent dosimeters (TLDs)



(See R. J. Tesarek *et al.*, IEEE NSS 2003)

- Radiation field is collision-dominated (> 90%) and scales with radius:

$$r^{-\alpha(z)}, \text{with } 1.5 < \alpha(z) < 2.1$$

- Ionizing radiation dose at r = 3 cm, |z| < 45 cm: 300 ± 60 kRad / fb^{-1}
- Use fluence conversion, 1 rad = 3.87×10^{7} MIPs/cm^2, to predict integrated dose

Radiation Damage in Silicon

Two general types of radiation damage

- "Bulk" damage due to physical impact within the crystal
- "Surface" damage in the oxide or Si/SiO_2 interface

Cumulative effects

- Increased leakage current (increased Shot noise)
- Silicon bulk type inversion (n-type to p-type)
- Increased depletion voltage
- Increased capacitance

Sensors can fail from radiation damage by virtue of…

- Noise too high to effectively operate (leakage current)
- Depletion voltage too high to deplete
- Loss of inter-strip isolation (charge spreading)

Ratio of signal/noise is the important quantity to watch

Radiation Damage in Silicon

Two general types of radiation damage
- "Bulk" damage due to physical impact within the crystal
- "Surface" damage in the oxide or Si/SiO_2 interface

Cumulative effects
- Increased leakage current (increased Shot noise)
- Silicon bulk type inversion (n-type to p-type)
- Increased depletion voltage
- Increased capacitance

Sensors can fail from radiation damage by virtue of…
- Noise too high to effectively operate (leakage current)
- Depletion voltage too high to deplete → *Biggest worry for Rad Damage in CDF*
- Loss of inter-strip isolation (charge spreading)

Ratio of signal/noise is the important quantity to watch

Bulk Damage

Bulk damage from hadrons displacing primary lattice atoms (for E > 25 eV)

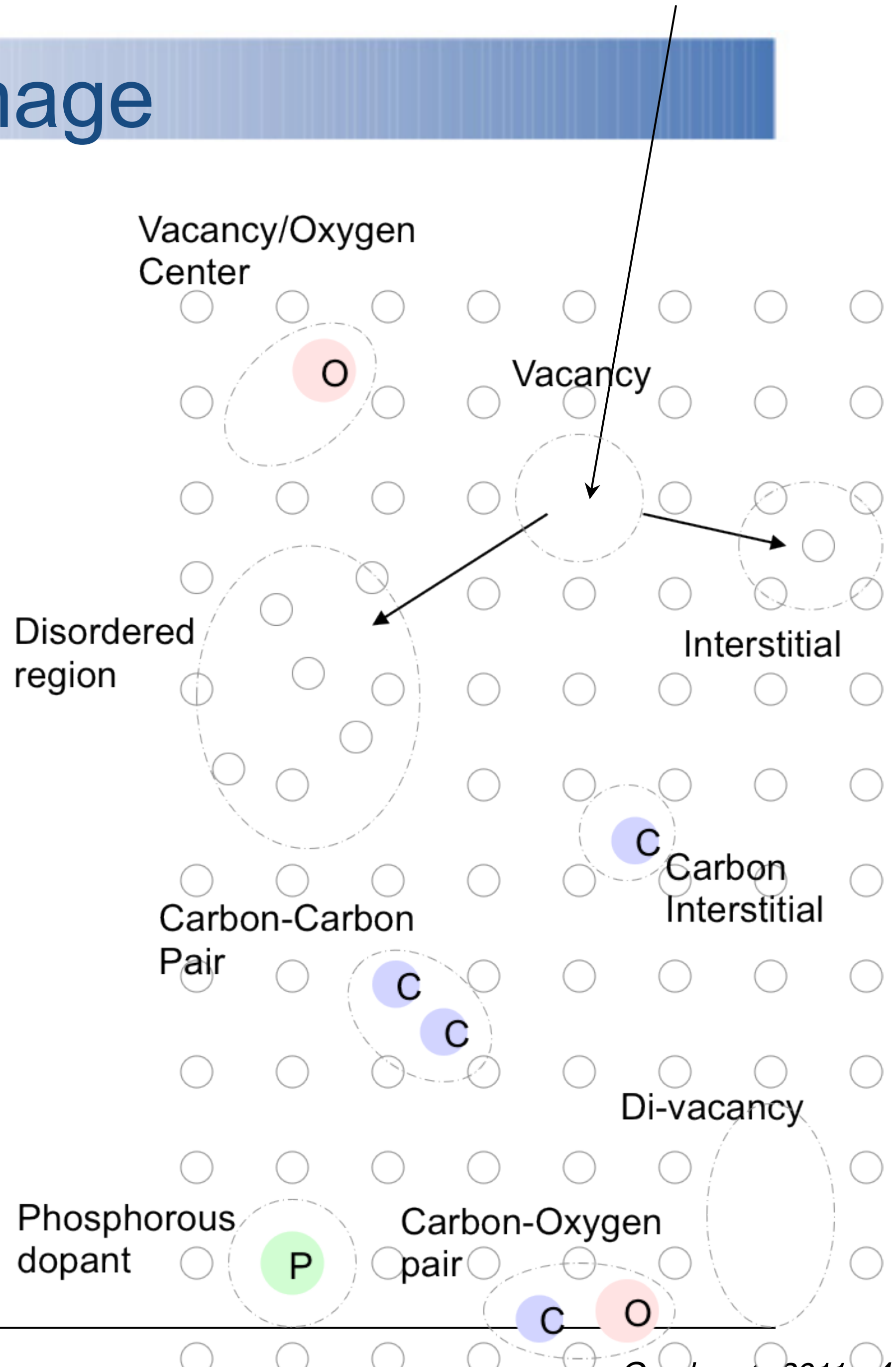
- Results in silicon interstitial, vacancy, and typically a large disordered region
- 1 MeV neutron transfers 60-70 keV to recoiling silicon atom, which then displaces ~1000 atoms

Defects can recombine or migrate through the lattice to form more complex and stable defects

- Annealing can be beneficial, but…
- Defects can be stable, unstable, or bi-stable

Displacement damage is directly related to the non-ionizing energy loss (NIEL) of the interaction

- Varies by incident particle type and energy



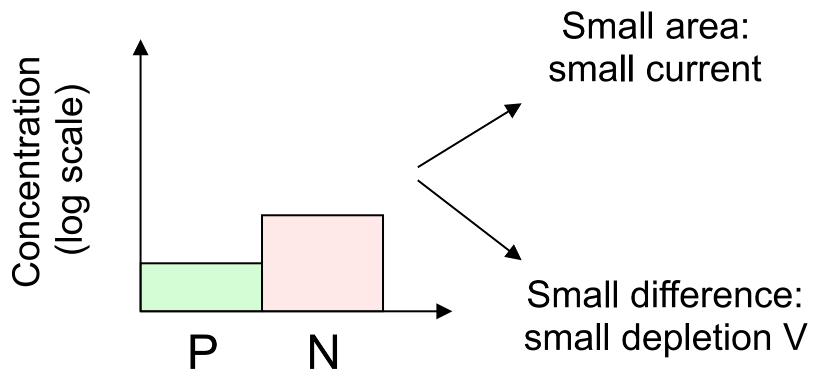
Bulk Damage Effects (Simple View)

Leakage Current:

$\Delta I = \alpha(t)\Phi V$

- Current depends on $\alpha(t)$ (annealing function), V (volume), and Φ (fluence).
- Annealing reduces the current
- Independent of particle type

Before Irradiation:

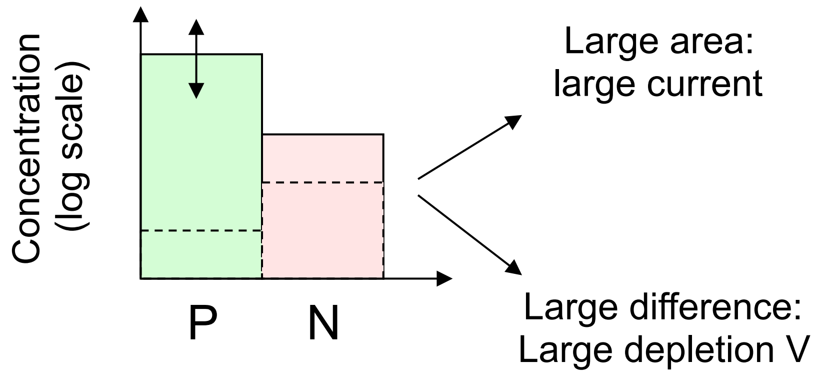


Depletion Voltage:

$V_{dep} = q|N_{eff}|d^2/2\varepsilon\varepsilon_0$

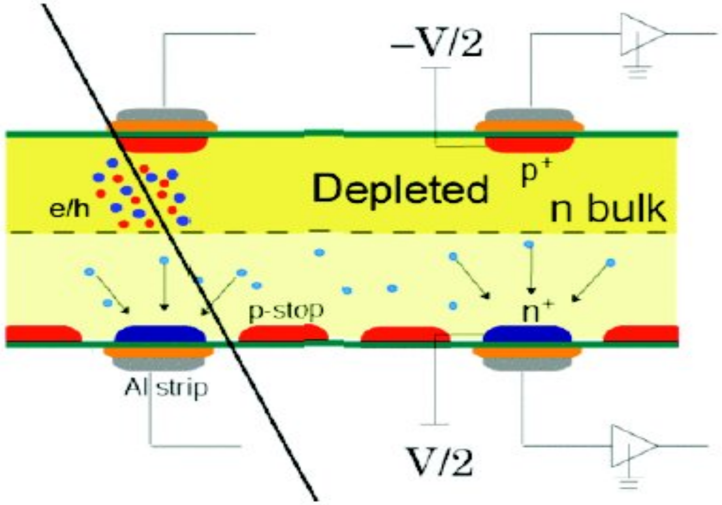
- Depends on effective dopant concentration ($N_{eff} = N_{donors} - N_{acceptors}$), sensor thickness (d), permitivity ($\varepsilon\varepsilon_0$).
- Depletion voltage is often parameterized in three parts: Short term annealing (N_a), stable component (N_c), and Long term reverse annealing (N_Y)

After Irradiation:

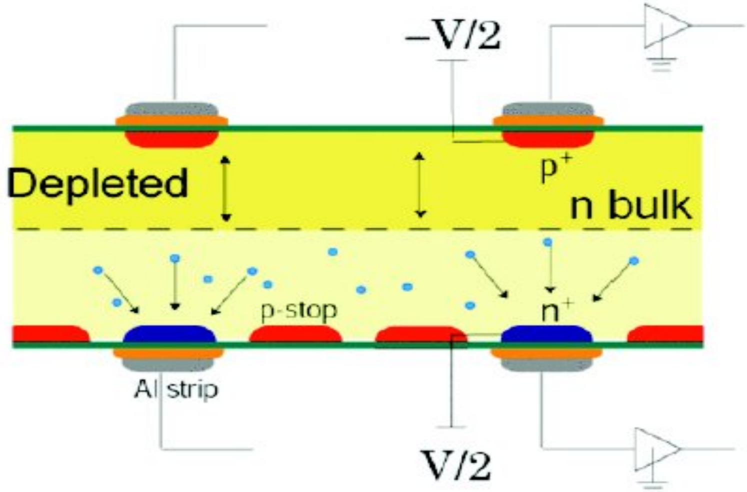


Depletion Voltage Measurements

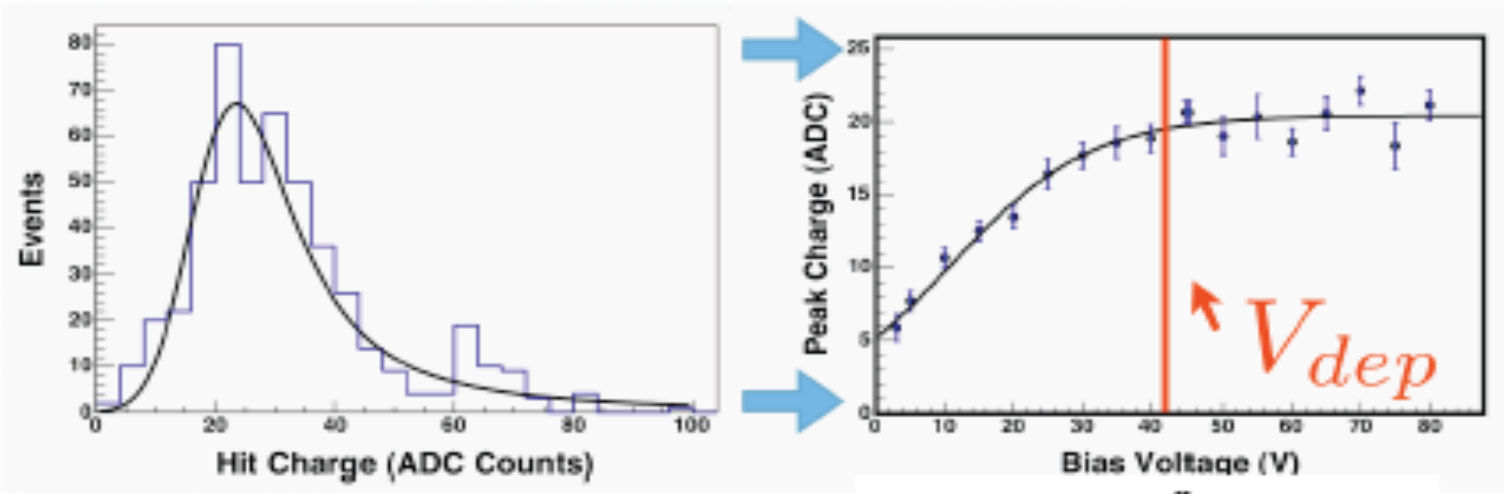
- **From charge (signal) collection efficiency:**
  - Charge collection is proportional to the depleted volume
  - Fully depleted sensor → charge collection efficiency saturates
  - Extracted track residual information



- **From noise at the n-side:**
  - Thermal noise from free carriers on the n-side is reduced with depletion (on the p-side)



Depletion Voltage – Signal vs Bias



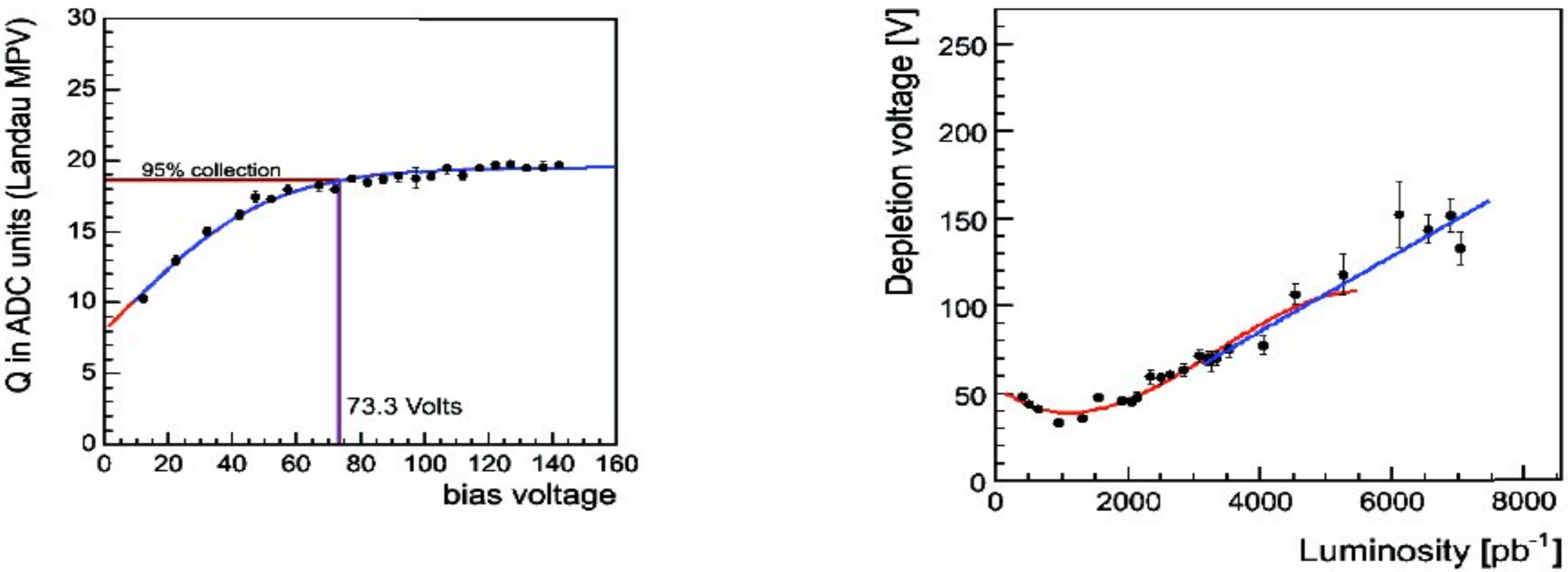
$$q_0 + \frac{q_A}{1 + e^{-2.944439}\, e^{-w\,(V - V_{dep})}}$$

Fit signal charge (hits on tracks) to Landau ⊗ Gaussian

Fit peak charge vs bias voltage to a sigmoid

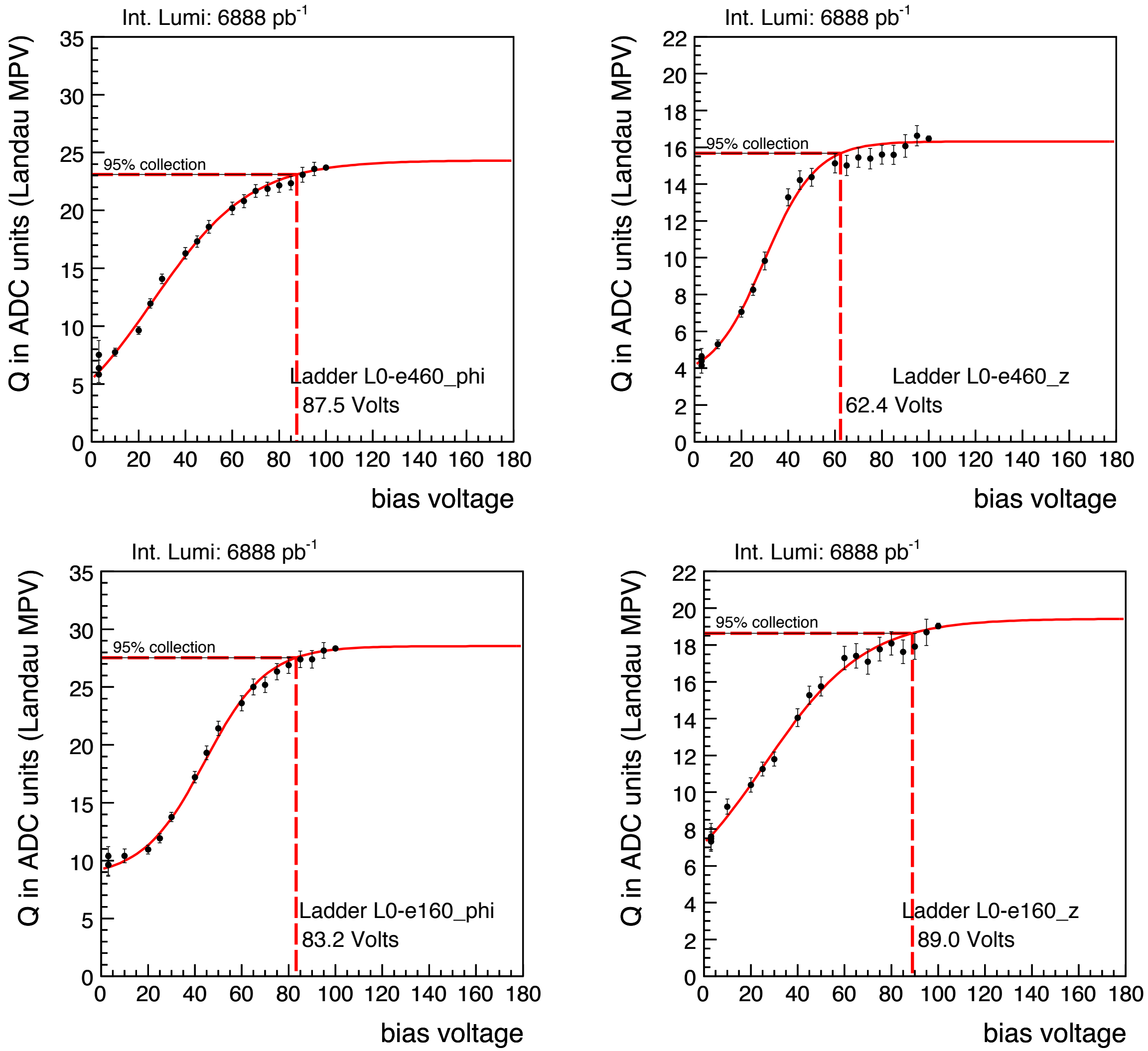
Depletion Voltage – Signal vs Bias

- Plot charge for different bias voltages
- Define depletion voltage, V_d , as voltage that collects 95% of the charge at the plateau



- Depletion Voltage as a function of integrated luminosity
  - 3rd order polynomial fit around the inversion point
  - Linear fit to extrapolate to the future

Depletion Voltage Extraction from Signal

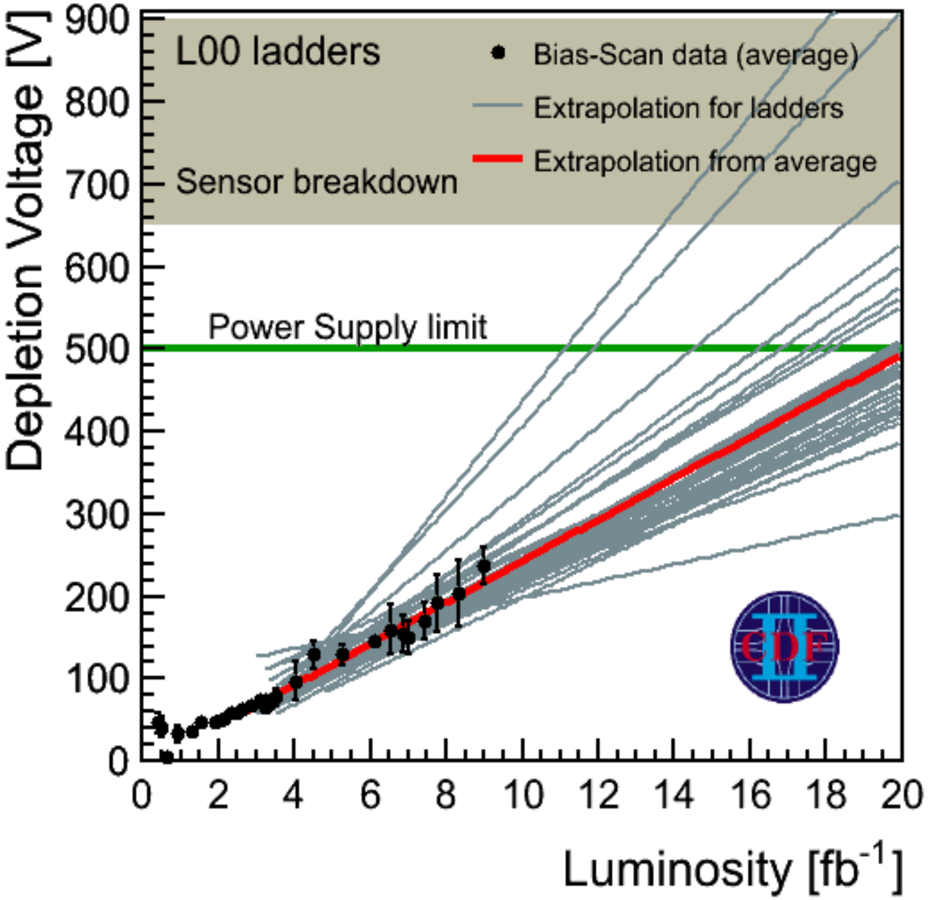


Robero Ballarin thesis
(CIEMAT Madrid)

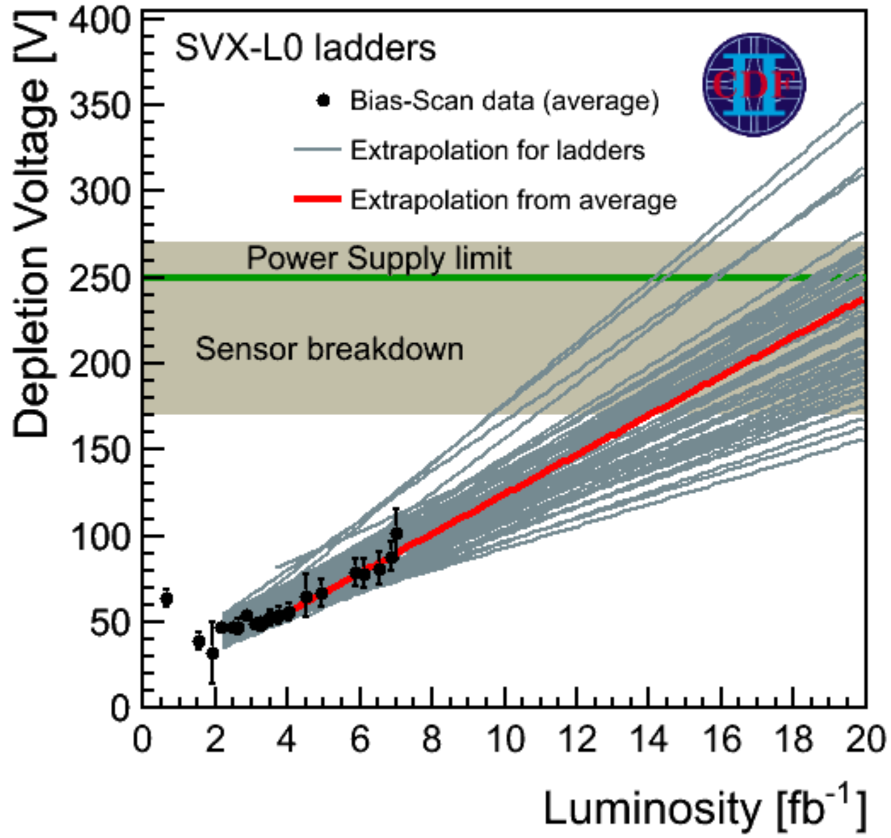
95% signal "Depletion Voltage" probably not the same as that from CV, Hamburg…

Preliminary Depletion Voltage Projections

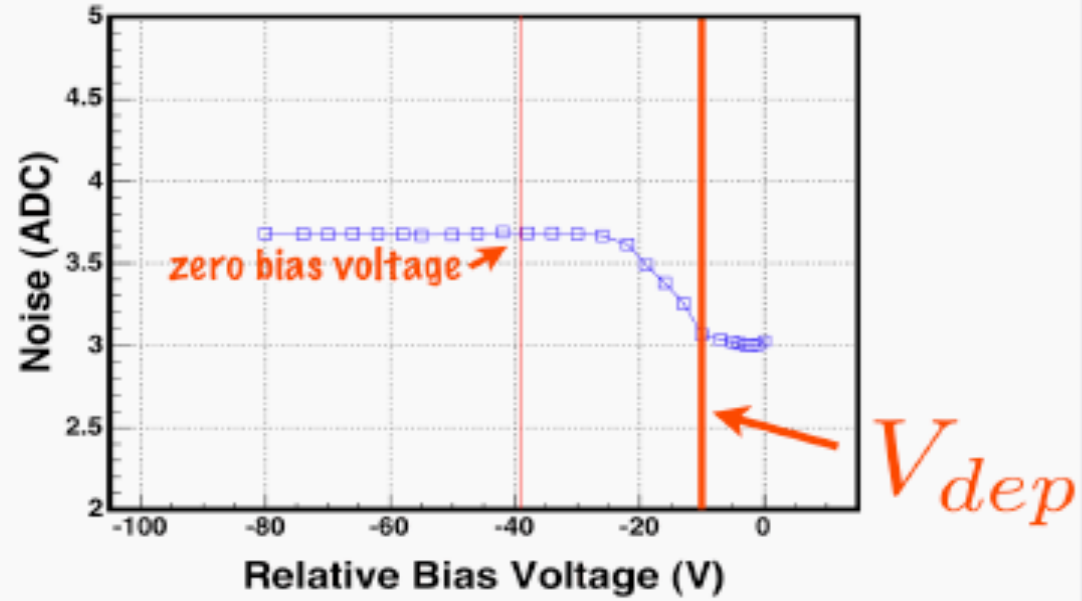
Prediction for L00



Prediction for SVX-L0



Depletion Voltage – Noise vs Bias



Find average dnoise vs bias voltage

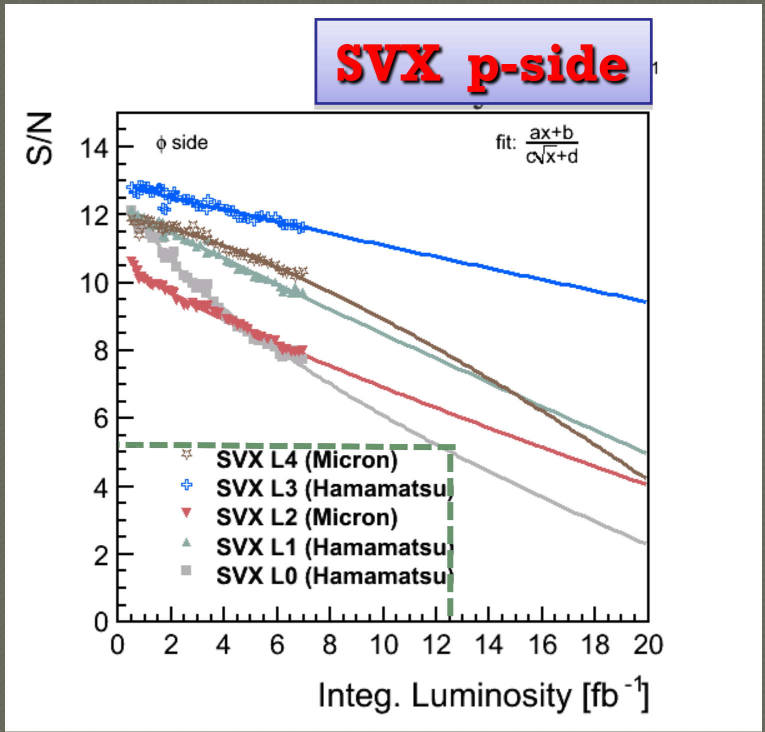
Depletion voltage taken as interpolation to 104% of minimum value

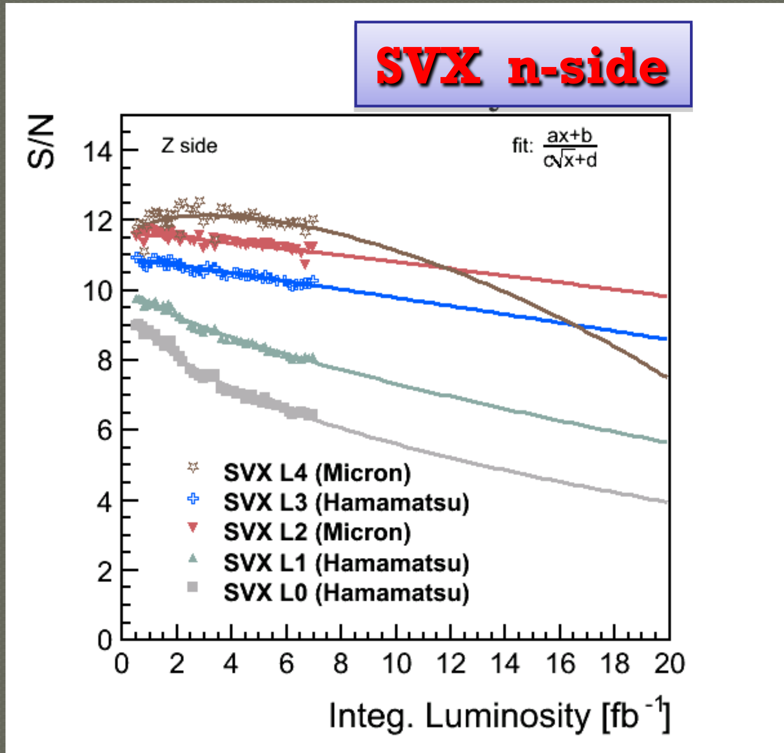
GOOD: does not require beam time

BAD: not possible for single side strip or after inversion type

Signal / Noise Measurements

- Signal from J/ψ → $\mu^+\mu^-$ tracks
- Noise measured with bi-weekly calibrations
- Extrapolations assume fully depleted sensors

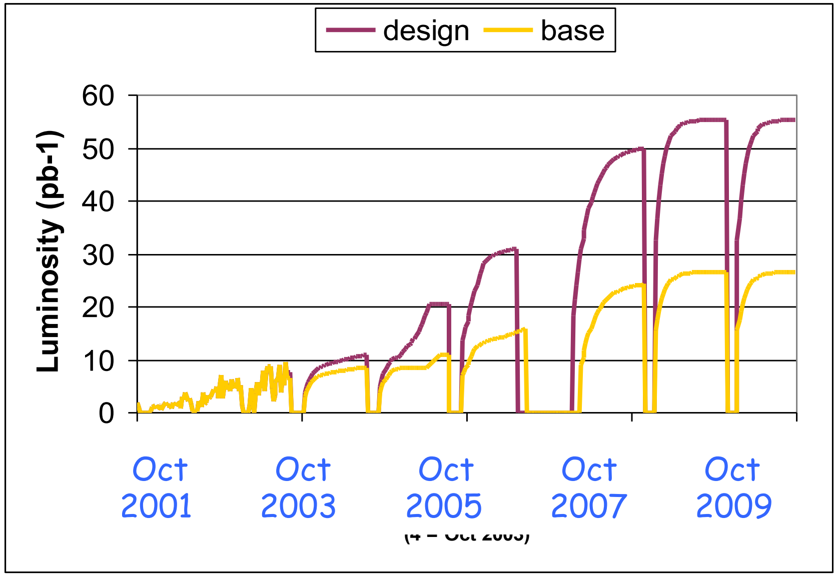




2003 Luminosity and Temperature Model

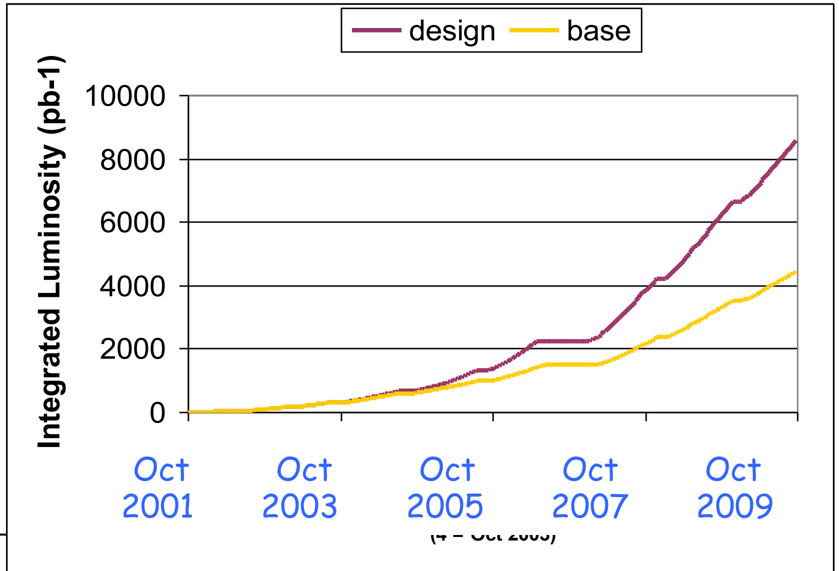
Luminosity Model provided by the Tevatron Beams Division (July ’03)

- “Design” goal is ~6.5 fb^{-1} by mid 2008
- “Base” goal is ~3.6 fb^{-1} by mid 2008
- Expected shutdown periods included
- Numbers are far more realistic than in the past… unfortunately also lower

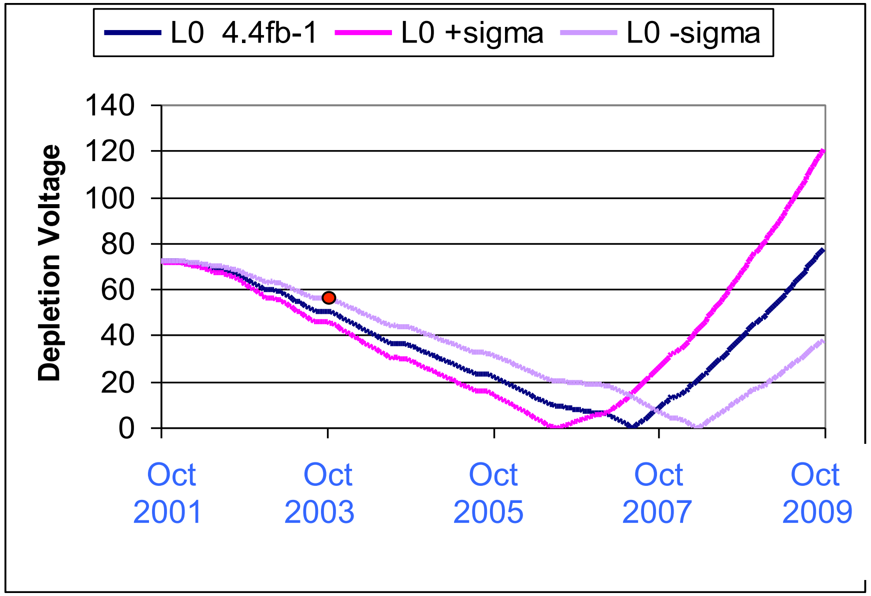


Temperature modeled on current operating conditions

- Chiller temperature is –6 °C
- Warm parts of SVXII silicon are 12±2 °C cold, 16 °C warm (design temperature)
- We can probably go colder

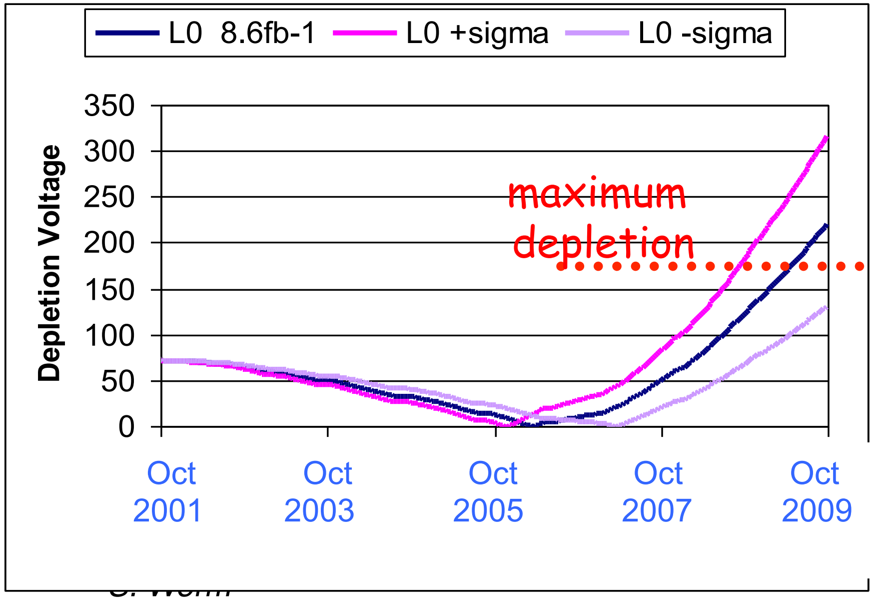


2003 Depletion Voltage Results



Results for “Base” luminosity

- Indicates full depletion throughout RunIIa
- Bands indicate approximate errors
- Red dot is measurement from noise study



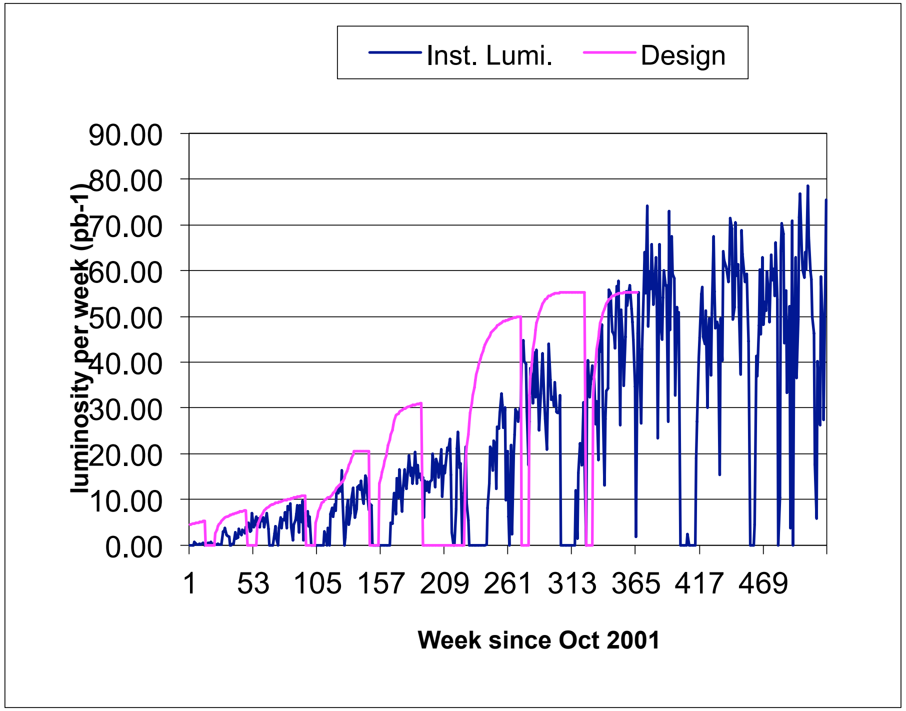
Results for “Design” luminosity

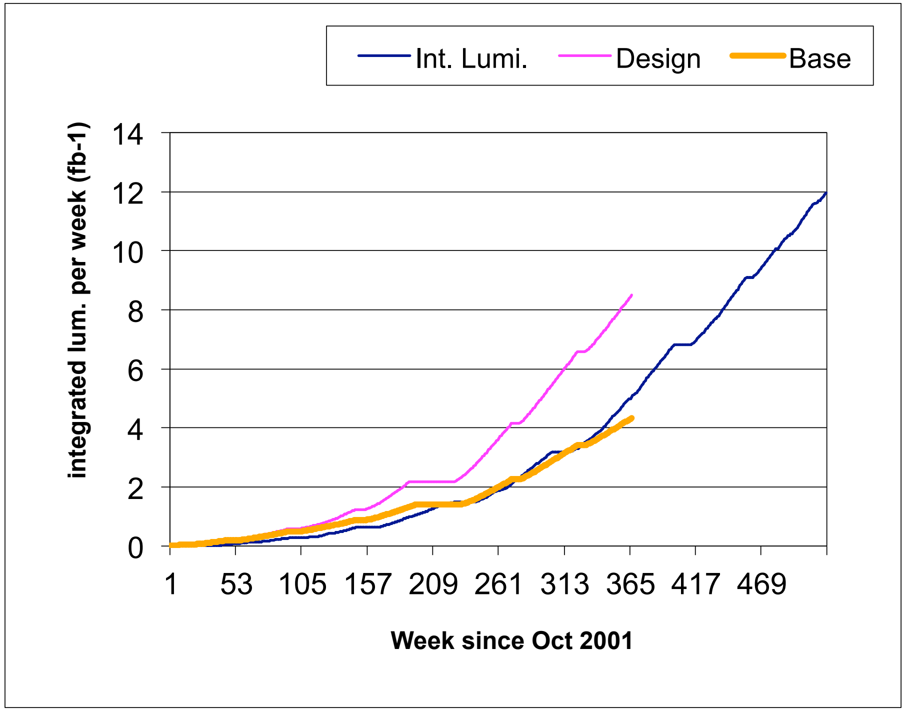
(assumes reasonable TeVatron improvement)

- Silicon inner layer will die from radiation
- Long term annealing becomes important
- Errors are rather large, driven by large ladder to ladder RMS

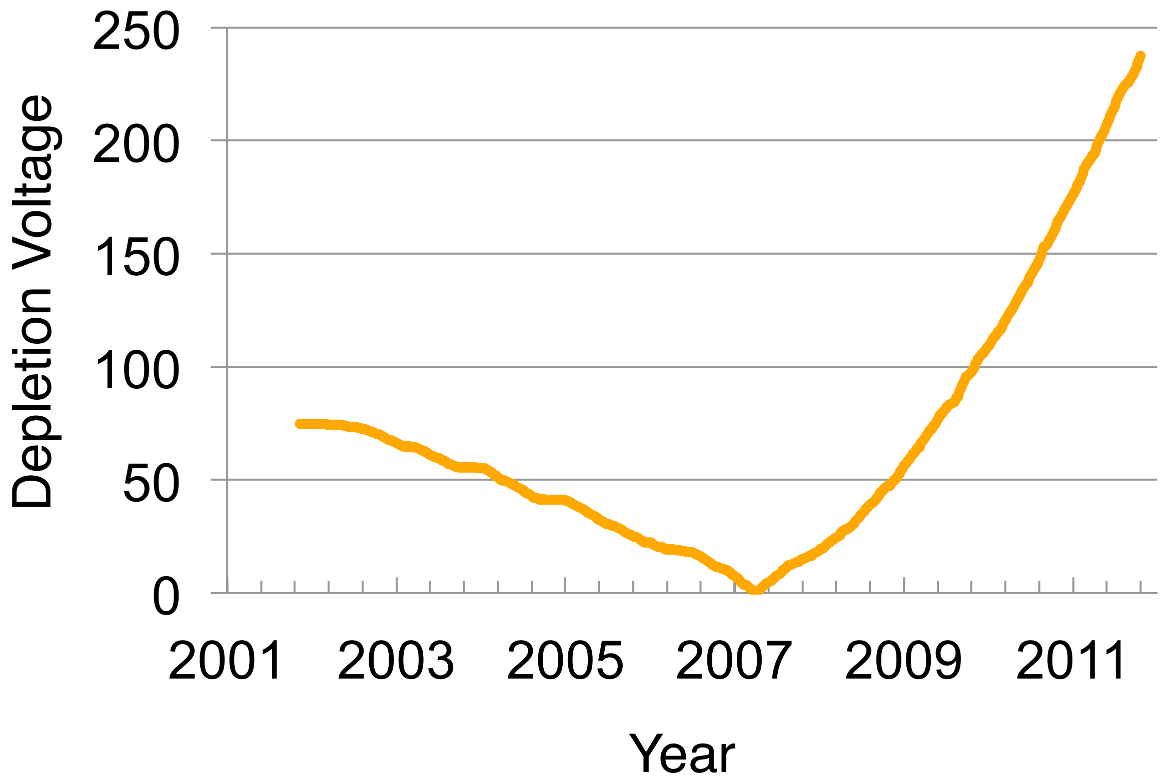
CDF Luminosity 2001-2011

Integrated Lumi matches “base” goals from 2003 (not “Design”)





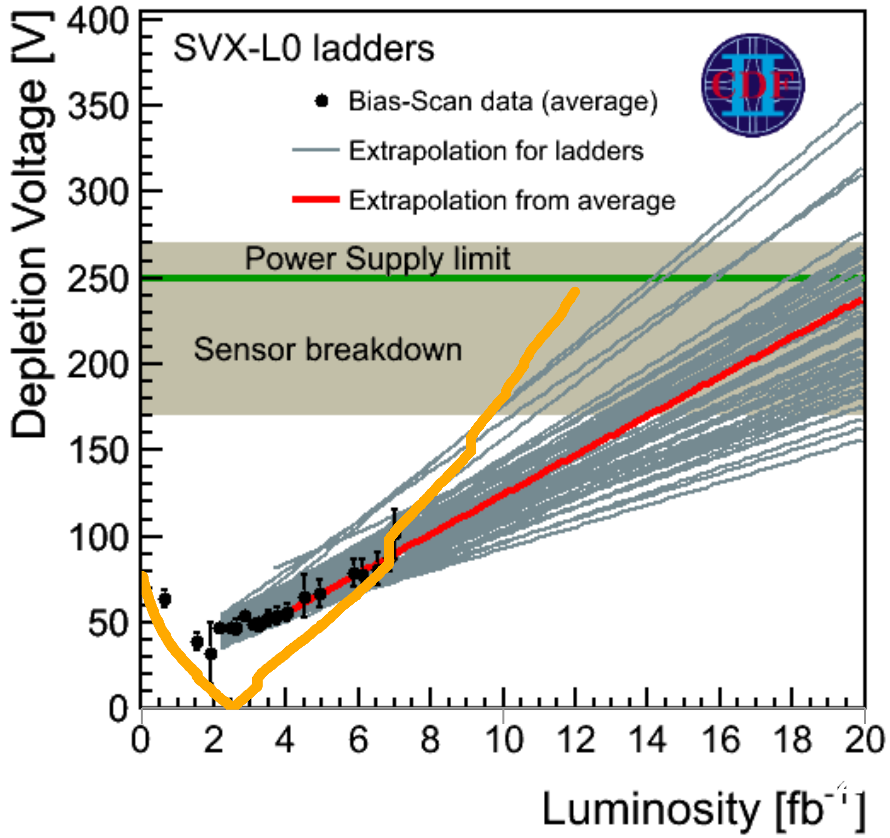
Hamburg Model Prediction – L0 CDF



Temperature Assumptions

- Didn't use detailed temperature profile; estimated by setting nobeam periods to warm
- Temperature varies across sensor: picked highest value
- After ~2007 ran colder: -10C at chiller, +8C for sensor

How does it compare?



…not very well!

Why so bad…?

Delivered Luminosity monitored, but hard to connect to damage in Si

- Extrapolation from Lumi to 1 MeV neutron equiv approximate at best

Temperature

- Temperature not well known, and varies across the modules
- No temperature data for study; just set no-beam periods to “warm”

Model Problems

- “Depletion voltage” a fairly arbitrary concept
- Damage parameters extracted from testbeam in 1997 probably wrong
- Simple “Hamburg” model difficult to apply to real experimental conditions
- Long-term annealing not so important?

As we found early on… trust the data, not the simulation.

The Real Issues for CDF SVXII Longevity

Common failure modes:

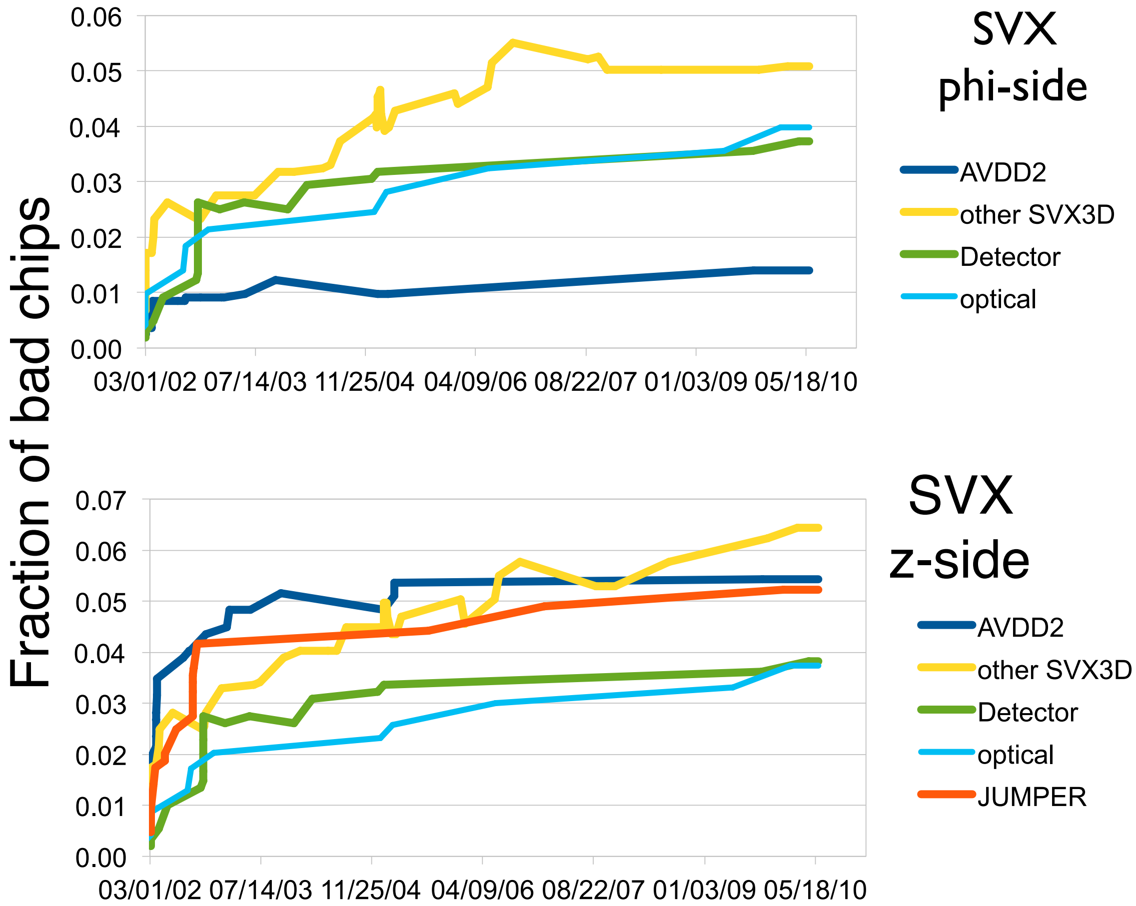
Detector includes port cards, junction cards, cables, and the sensors themselves.

Optical is bit errors from the internal DOIM data transmitters

Jumper is SVX3D chip failures due to wire bond resonances

AVDD2 is a SVX3D chip failure mode caused by thermal cycles

Other SVX3D includes all other chip failure modes



Conclusions

Online monitoring is critical, and radiation damage longevity predictions can be extracted from this with a minimum of modelling

Difficult to track all necessary parameters in order to model damage from first principles

Conclusion from CDF: monitor noise/currents and depletion/signal and trust the data, not the simulation.


F
A
R
E
W
E
L
L
C
D
F

CLEO III Silicon Sensor

Double-sided silicon wafer by Hamamatsu

2 x 511 channels, wafer 53.2 x 27 x 0.3 mm

Strip spacing 50 μm r-ϕ, 100 μm z.

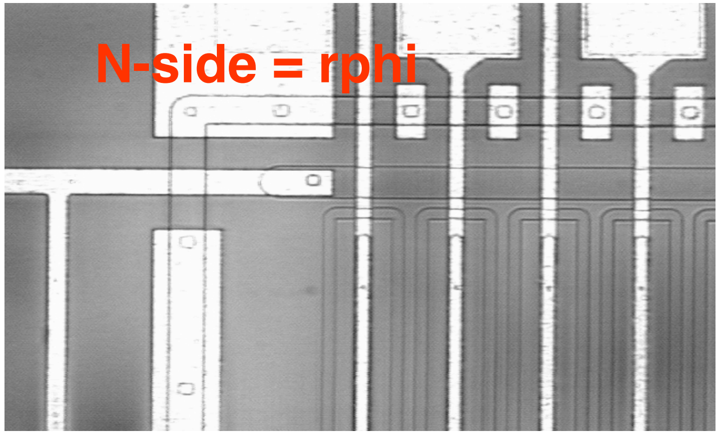
Ladder length requires low strip capacitance. 9 pF in p and n achieved,

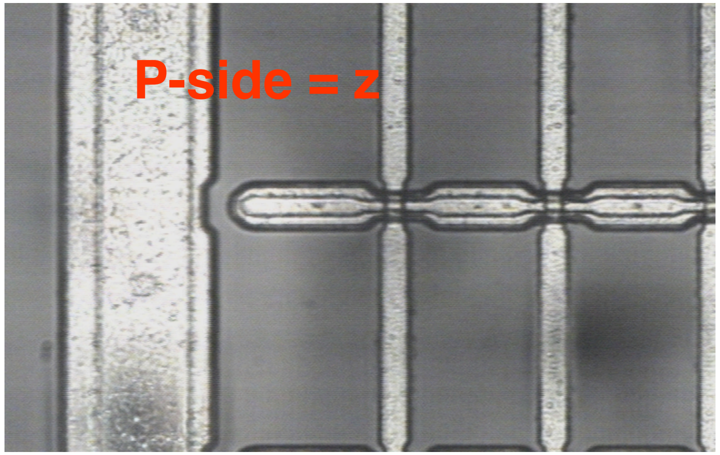
N-side with pstops, atoll design, pstops punch-through biased.

P-side is double metal side. Hourglass design of metal layer overlap.

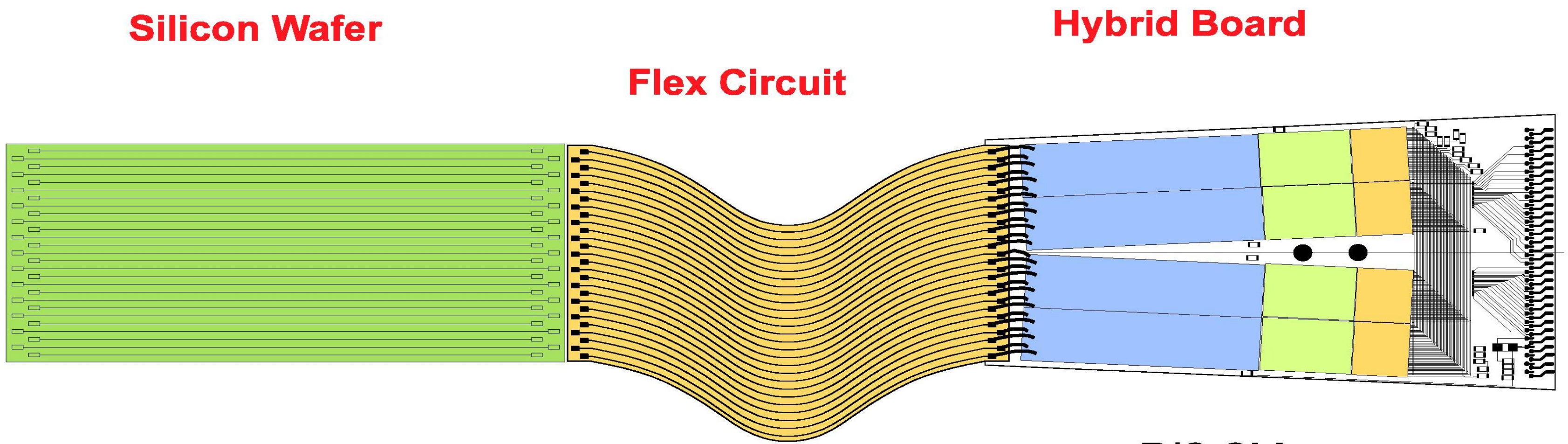
AC coupling capacitor and bias resistor on separate chip

Radiation damage constant(surface damage) 5 nA / kRad / (exposed) cm^2





Readout Chain



- **Double Sided**
  pside = z-side
  nside = r/phi side
- **511 channels / detector**

- **Cu/Au traces on Kapton Substrate**
- **511 channels + Bias lines**
- **Double Sided**
- **Two Flexes/detector**

- **R/C Chip**
  Quartz Wafer
  128 channels
- **Frontend**
  Preamp + Shaper
  Custom Chip
- **Backend**
  SVX_CLEO
  8 Bit ADC
- **Double Sided**

Modular Design of Wafers and Hybrids

Depletion Voltage Model – cont.

Long term (reverse) annealing is significant only at the end of the run

Parameter	Value
g_Y $[10^{-2}cm^{-1}]$	4.6 ± 0.3
g_C $[10^{-2}cm^{-1}]$	1.77 ± 0.07
N_{C0} $[10^{11}cm^{-3}]$	5.0 ± 0.2
E_a [eV]	1.31 ± 0.04
c $[10^{-13}cm^2]$	2.0

"Death" of the Silicon; Modeling the S/N

We expect that the inner silicon layers will eventually be unusable due to low S/N

- Displaced track triggering will be good to S/N = 8.
- B-tagging will be degraded at low S/N (in Run I, ε was lost below S/N ~6)

Noise

- Shot noise calculated from leakage current
- Chip noise measured in controlled irradiations

Signal

- Double-sided AC-coupled Si → voltage on caps
- ~170V maximum depletion, from burn-in
- Axial strips are on p-side; can't get axial info while underdepleted
- Depletion voltage estimates therefore critical
- Assume full charge collection throughout Run II

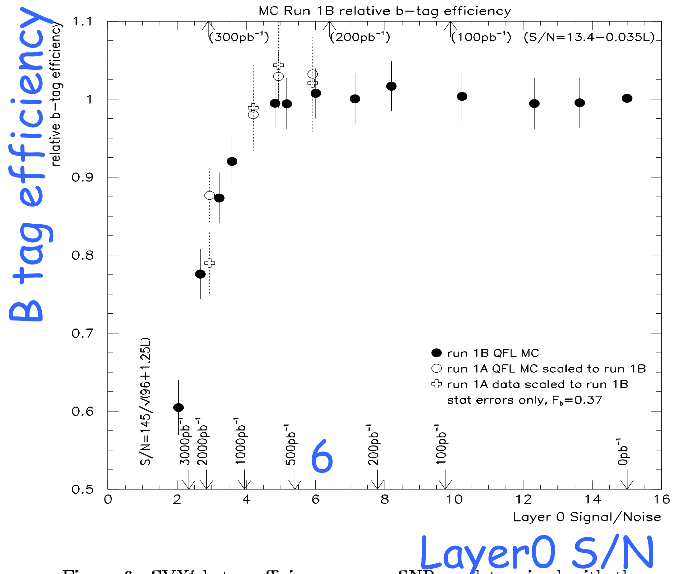


Figure 6: SVX′ b tag efficiency versus SNR as determined with the new simulation. Corresponding integrated luminosities are shown along the top of the plot for the linear, and possibly pessimistic, parametrization of SNR vs $\int Ldt$ in equation (3). The integrated luminosities for the "physical model" in equation (2) are indicated along the bottom of the plot. The errors shown are statistical and correlated as discussed in the text. The open cirles are the MC predictions for SVX at various points in run 1A, and are consistent with the run 1A data measurements shown as crosses (statistical errors only).

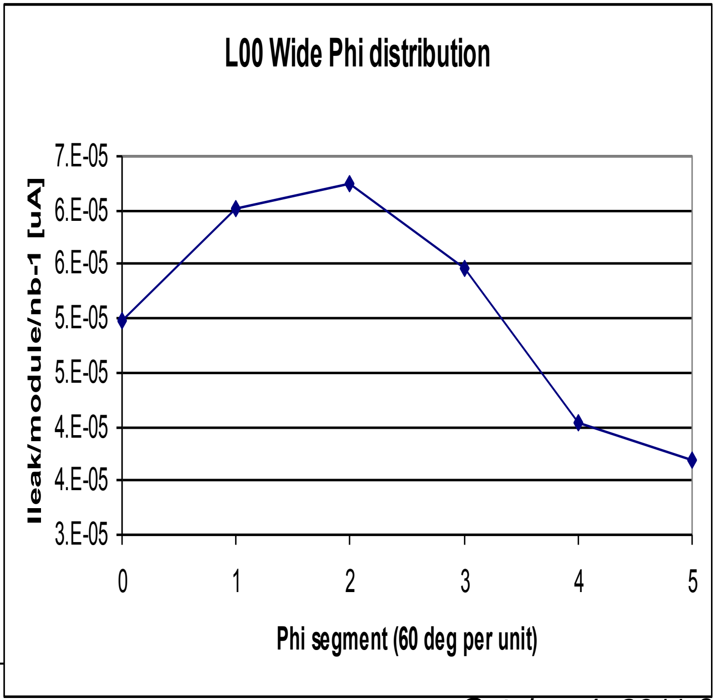
An example "Real World" effect: Beam Offset

The CDF detector and Tevatron beam are not perfectly co-axial

Assuming a $1/r^{1.6}$ radial dependence, the top sensors of LOO receive ~50% more radiation than the bottom ones.

Offset will be corrected in an upcoming shutdown

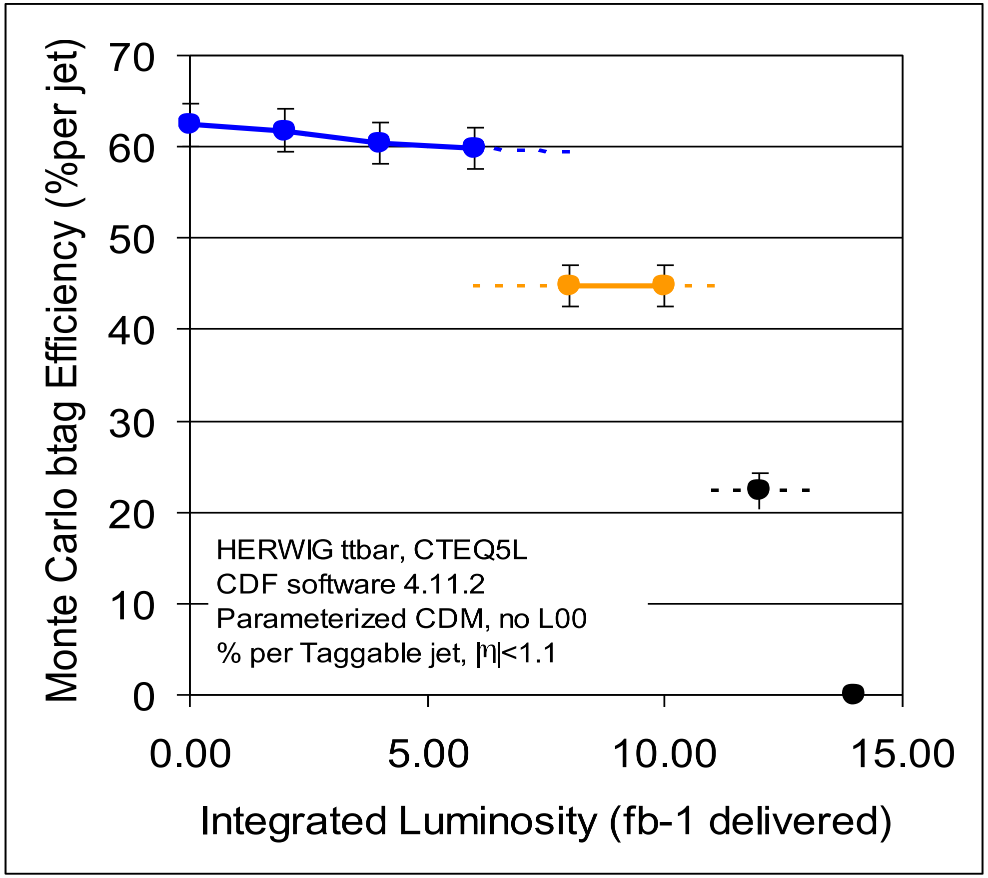
	x [mm]	y [mm]	x' [μr]	y' [μr]
SVXII	-1.0625	1.5003	756	-314
Beam	-1.8	4.5	600	100
difference	-0.74	3.00	-156	414



The models can be used as a guide, but the errors are often larger in the "real world"

Degradation in b-tag efficiency

(preliminary results)



Secondary Vertex Tagging (b jets)

- HERWIG Monte Carlo study
- Secondary vertex (b) tagged events
- Remove L0 from tracking at 6-8 fb^{-1} (orange points)
- Remove L1 at 10-12 fb^{-1}

Requirements:

- b is in the detector ($|\eta|<1.1$)
- b yields a jet w/ at least two tracks

L00 not included

- Not yet in the 'default' tracking
- Not studied yet for tagging

Results

- efficiency still good after S/N degraded
- L00 must be fully integrated and must survive to maintain tag efficiency