Aging and Radiation Damage in the CDF Run-II Silicon Detector

Michelle Stancari
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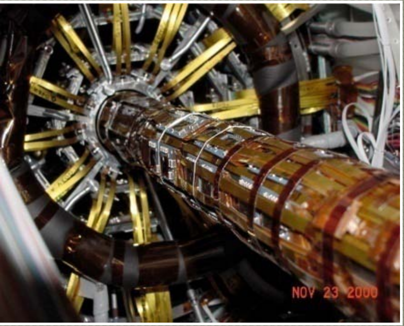
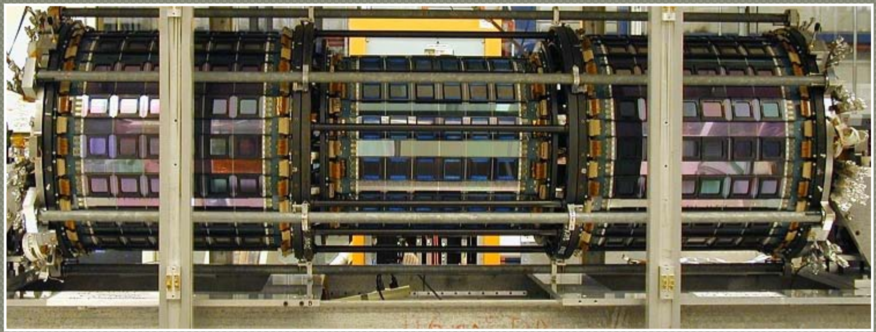




Outline

- Why study radiation damage?
- How does CDF monitor bulk radiation damage?
  - Signal to Noise ratio
  - Depletion voltage
- How is what we observe different than what we expected?
- Double junction model for irradiated sensors.

Beyond the scope of this talk

Surface radiation damage

- Low radiation dose effects due to accumulation of charge in the SiO_2 layer and the Si/SiO_2 interface.
- Changes the inter-strip capacitance
- Eventual breakdown behavior

Single Event Effects/Upsets

- Charged particles traversing integrated circuits often upset their programming (readout electronics and power supplies in the collision hall)
- Usually fixed by a crate reset or re-initialization
- Causes downtime and sometimes broken modules

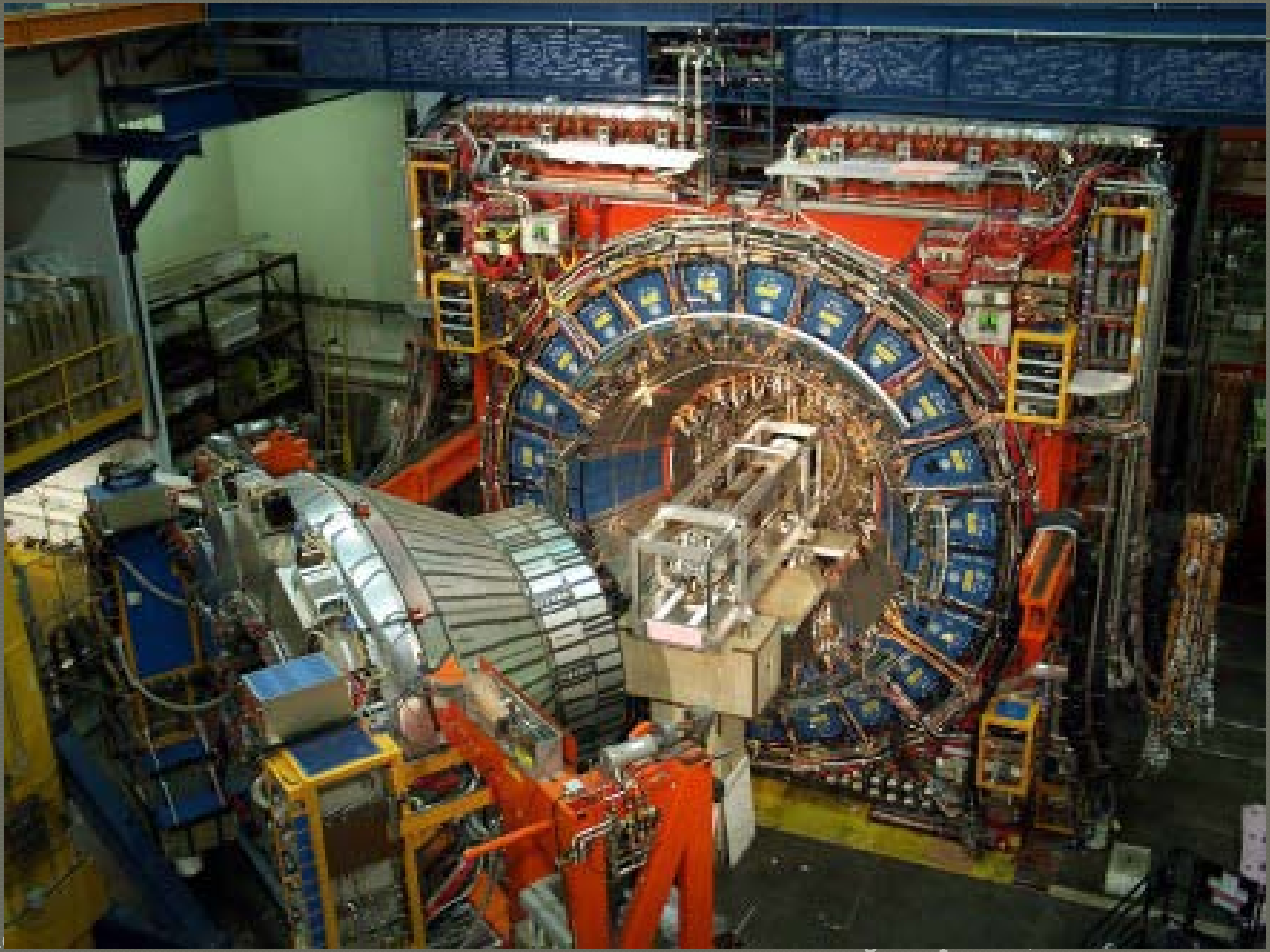
Radiation affects all solid state devices!

- Readout ASICs – data leaves the bore in digital form. The noise from the readout chips increases with radiation dose.
- DOIMs – data leaves the bore in optical form. The light output of these edge-emitting laser diodes decreases with dose.

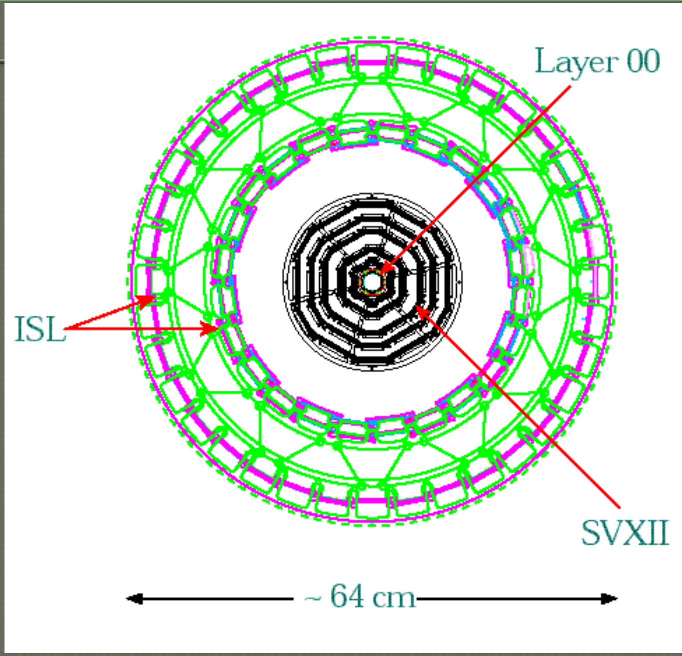
Why talk about radiation damage?

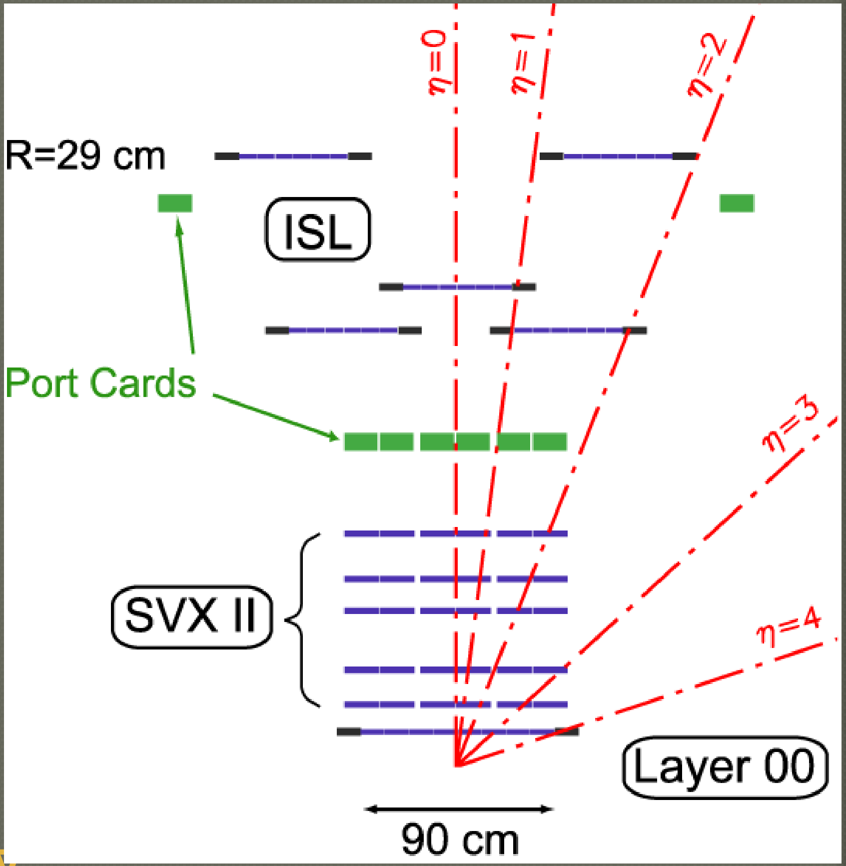
- LHC experiments want to know how long their silicon will last
- Simulations of radiation effects in silicon detectors need data to tune on
- Tevatron data are unique
  - slow irradiation over a long period of time (**the Tevatron**) is not the same as heavy irradiation in a short period of time (**beam tests**)?
  - Irradiation while biased is not the same as irradiation without bias voltage?
  - Tevatron detectors irradiated more than intended because the upgrade was cancelled – unplanned opportunity to study detector degradation.

CDF II Silicon Detectors



CDF-II Silicon Detectors

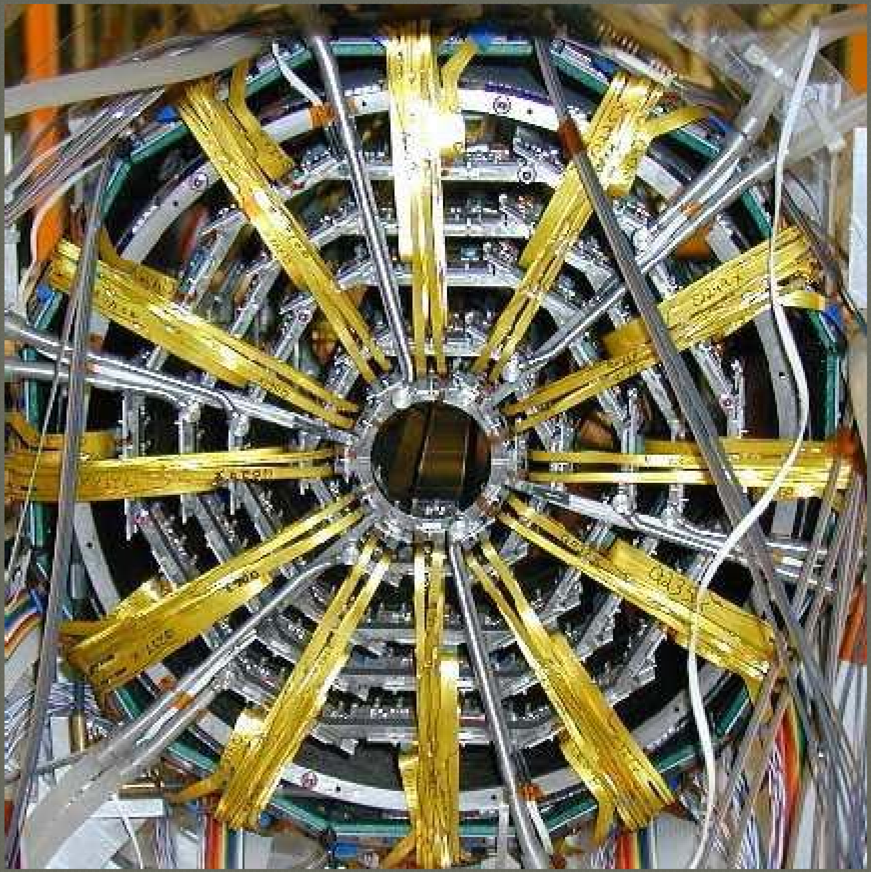




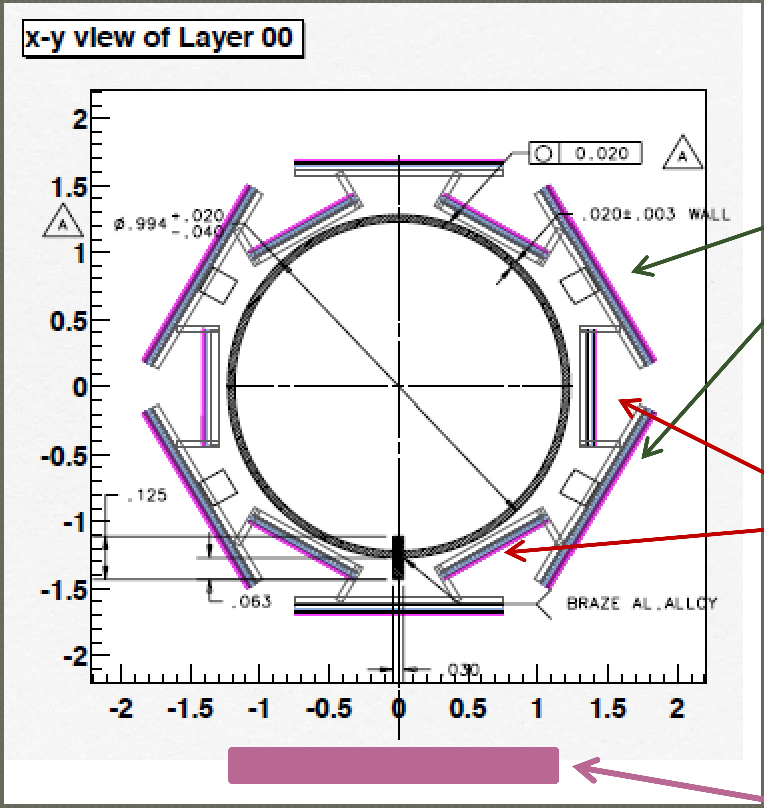
- 8 Layers, 704 ladders, 722432 Chans
  - Layer 00 (L00): 1 Single Sided layer
  - SVXII: 5 Double Sided Layers
  - ISL: 2 Double Sided Layers
- THIS TALK: L00 and SVX-L0 only – most vulnerable to radiation

SVX details

- 5 layers of double sided sensors
  - Layers 0, 1, and 3 – Hamamatsu, 90 stereo
  - Layers 2 and 4 – Micron, small angle stereo
- NOT actively cooled



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

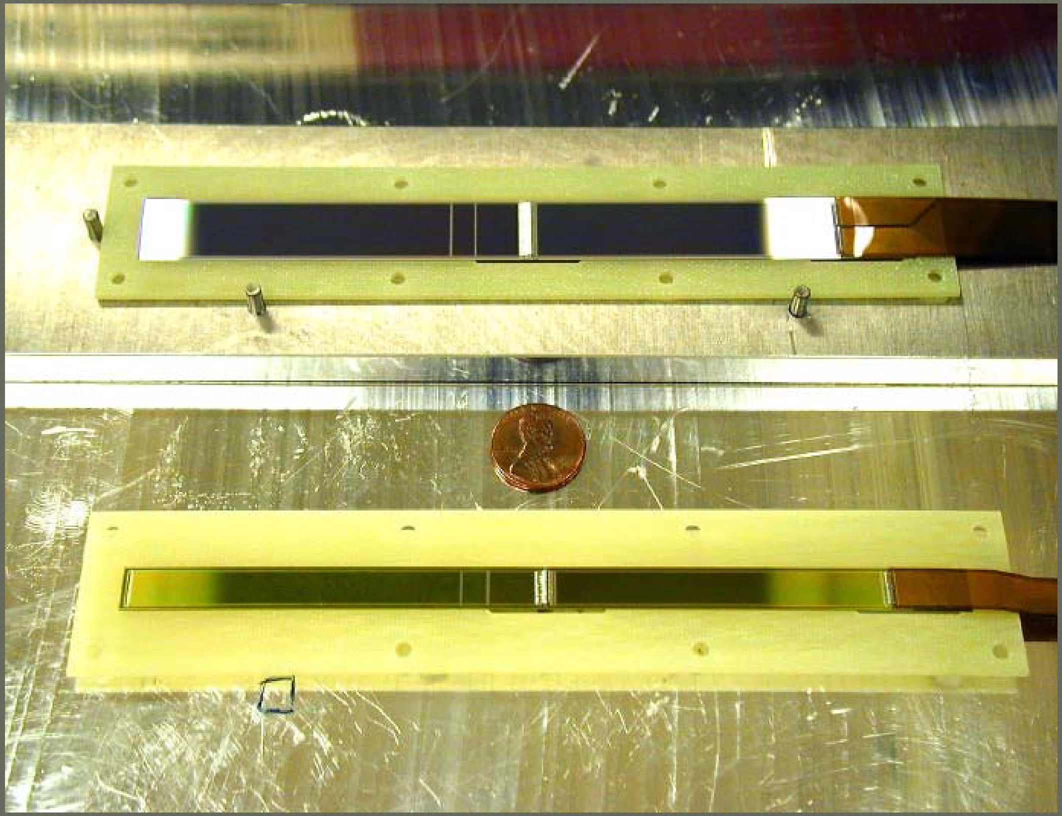
L00 details

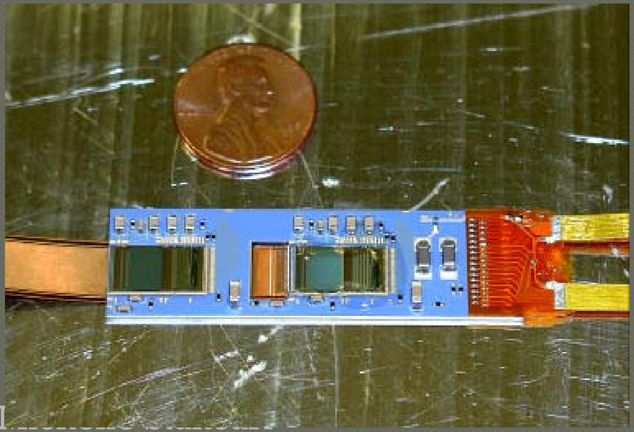
<u>All CMS and ATLAS strip silicon sensors were fabricated with the same technology as L00</u>

("p+ on n bulk", <100>-oriented, radiation tolerant silicon)

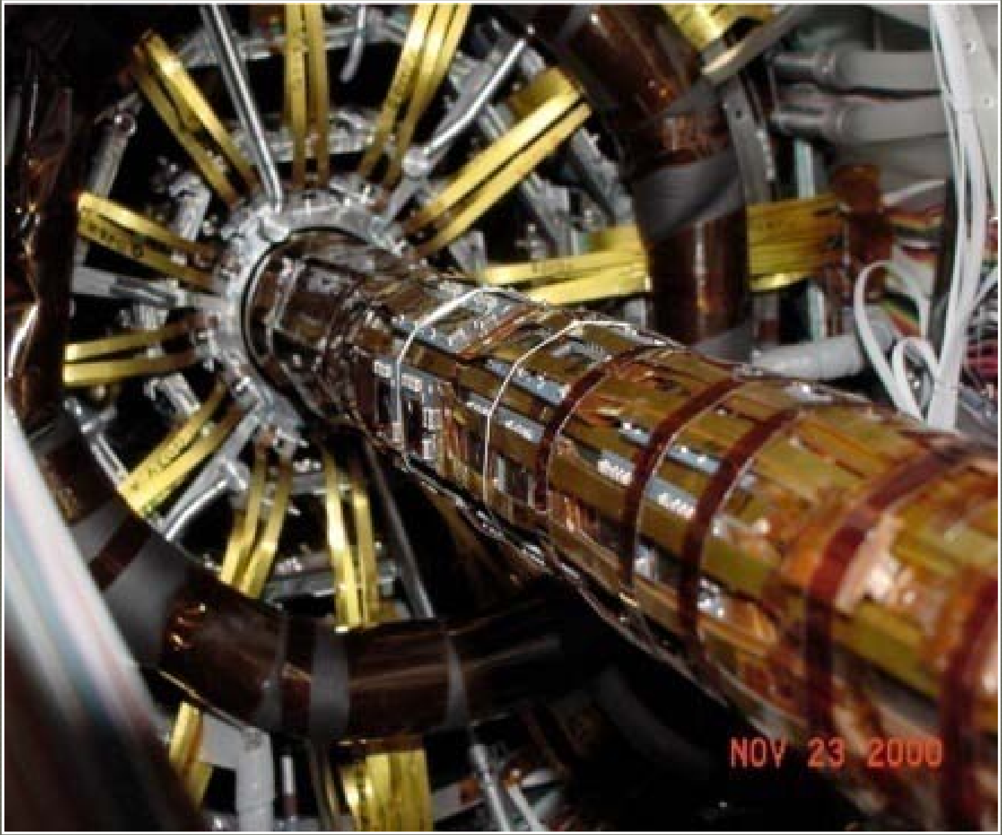
- L00 intended to outlast SVX-L0
- Bulk properties of L00 are NOT different from SVX sensors
- Longer lifetime because . . . .
  - Stronger coupling capacitors (600V compared to 200V for SVX)
  - Reduced noise growth with radiation dose – actively cooled and hybrids outside tracking volume
- Two oxygenated sensors were included in the "narrows" as R&D, they are expected to suffer less bulk radiation damage

L00 photo album



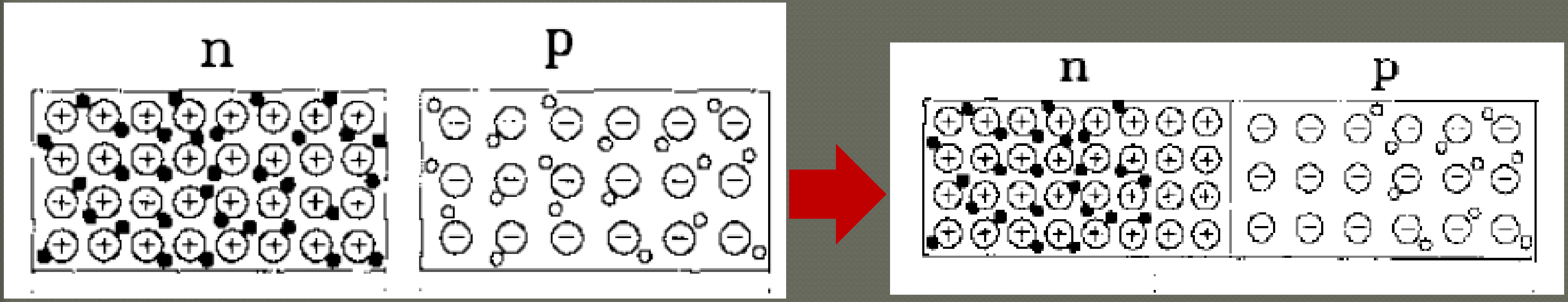


L00 and SVX



How Silicon Sensors Work

Silicon sensors can be thought of as simple, reverse-biased diodes. Start with a p-n junction.



⇒ Electrons drift into the p-region and holes to the n-region
⇒ Non neutral charge distributions near boundary in each region
⇒ The resulting electric field counteracts diffusion => equilibrium
⇒ The field sweeps away any movable charge carriers from the boundary

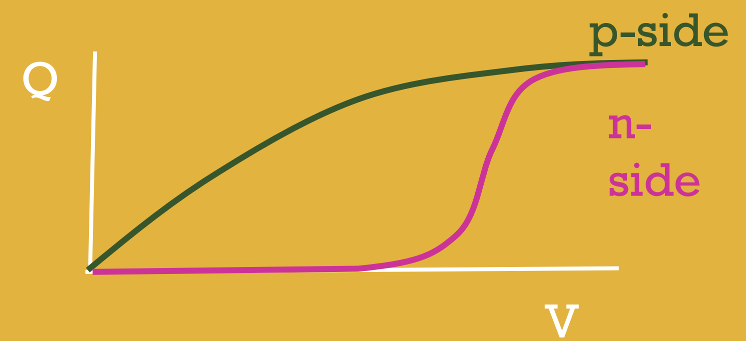
Lutz and Schwartz, ANRPS 45:295-335 (1995)

Working Principle

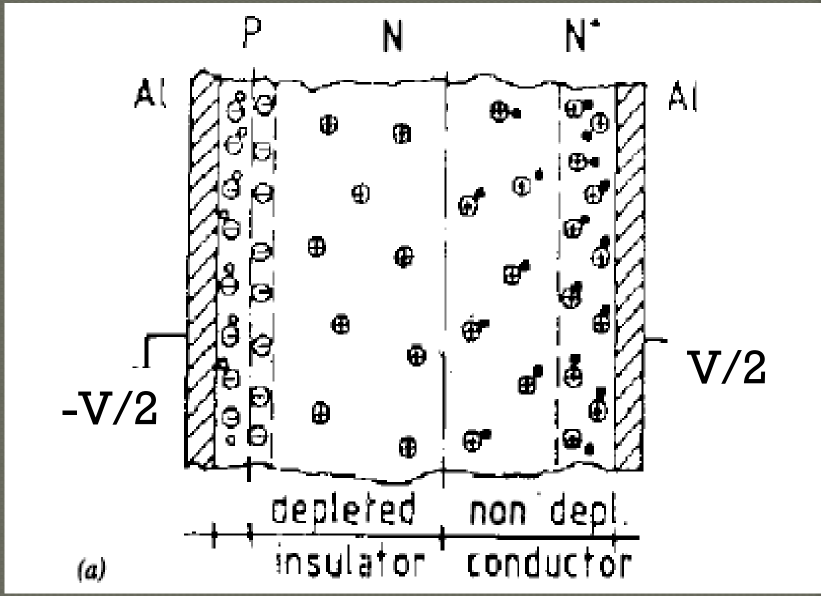
Now add reverse bias . . .

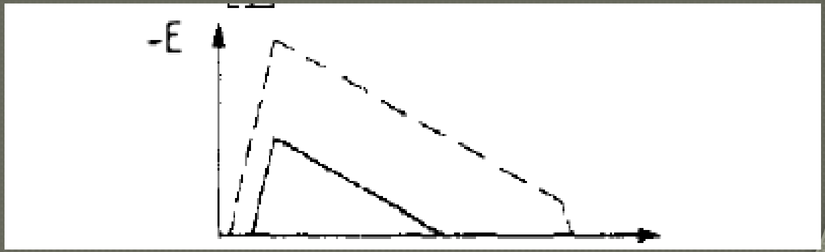
- DEPLETION: Free charge carriers are removed with enough voltage
- Electron-hole pairs generated in the depleted region are separated by the electric field and move toward the electrodes
- MIP generated e-h pairs form signals
- Thermally generated e-h pairs form a small amount of dark current

Behavior of un-irradiated sensor

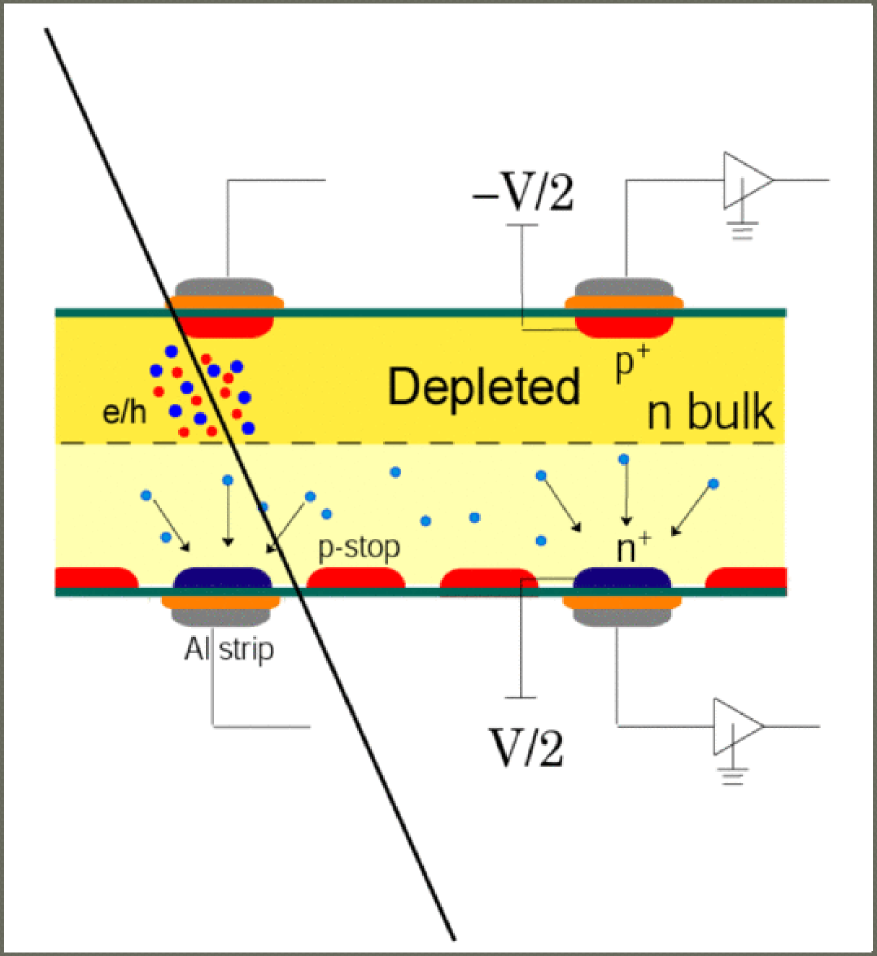


UNDER-DEPLETED SENSOR





Prettier Picture



Bulk Radiation Damage

<u>Bulk damage</u> is due to displacement of silicon atoms in the crystal lattice

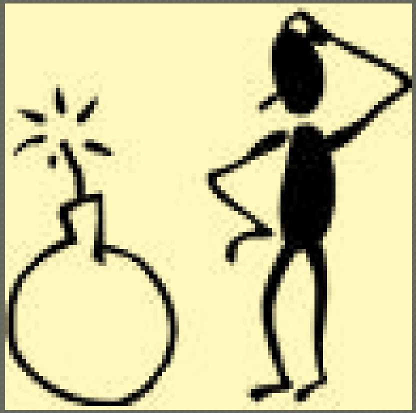
- ⇒ Amount of damage depends on temperature
- ⇒ Local distortion of lattice properties
- ⇒ Stable electron/hole energy levels between the conduction band and the valence band in the vicinity of the crystal defect
- ⇒ **Traps free charge carriers temporarily.**
  - Increase of bias current
  - Decrease in signal collected in integration window
  - Increase in depletion voltage

Operating Voltage Increases

S/N ratio decreases

How do sensors die?

. . . from bulk radiation damage

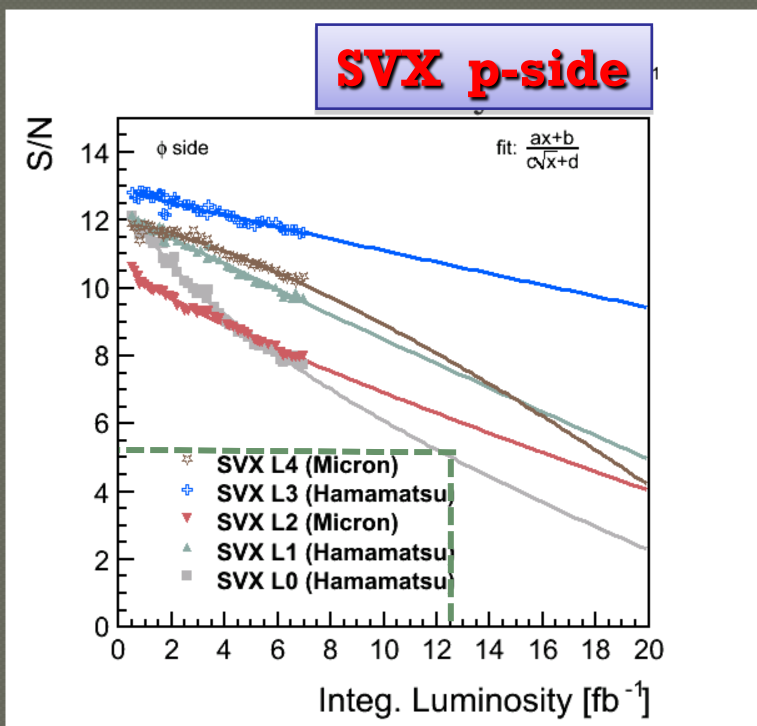


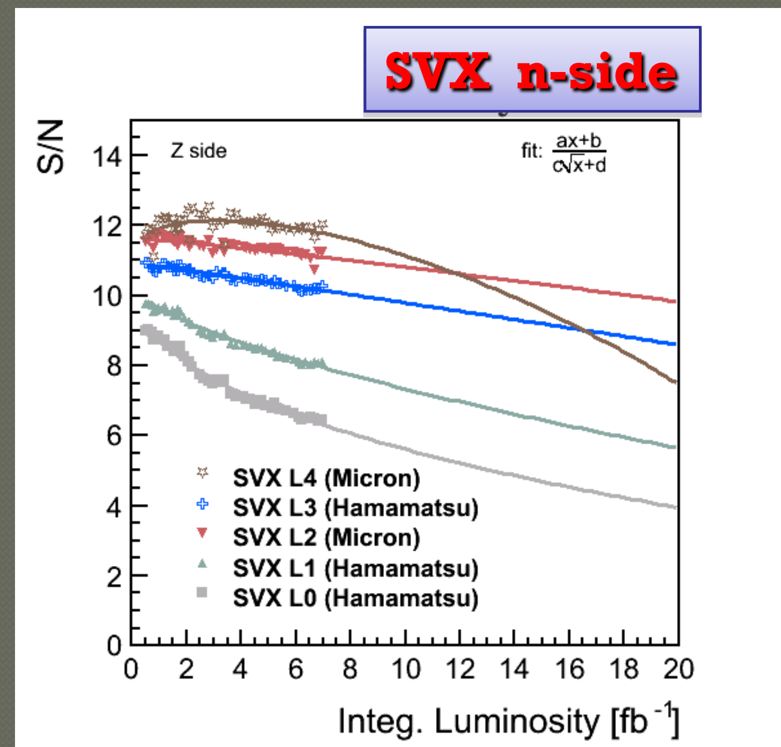
- S/N is too low to find hits

  (and/or to be used online in the first level trigger)
- The depletion voltage exceeds the maximum operating voltage
  - Sensor Breakdown (SVX – 200 V due to fragile coupling capacitors)
  - HV supply and/or cables (L00 – 500V)

Signal / Noise Measurements

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





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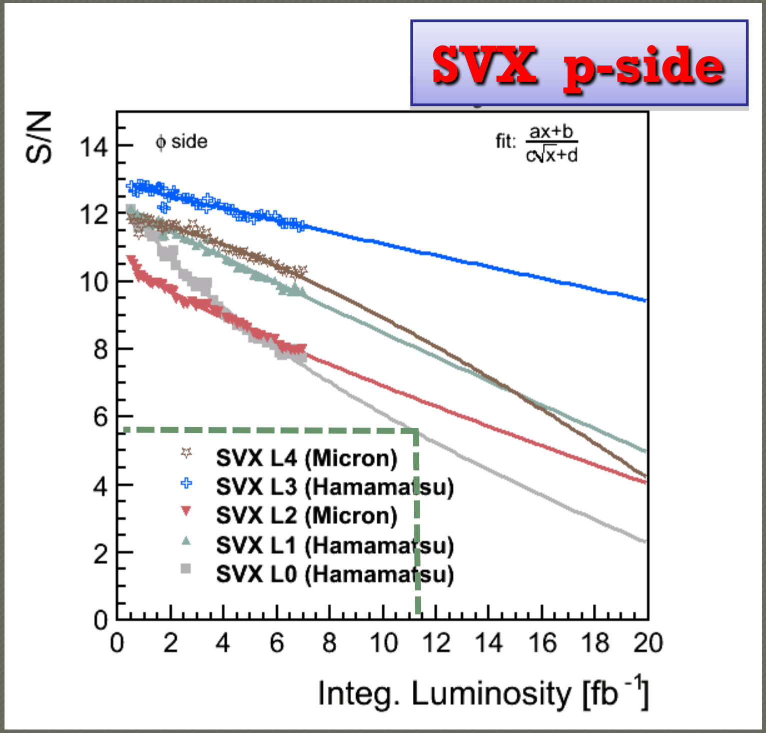
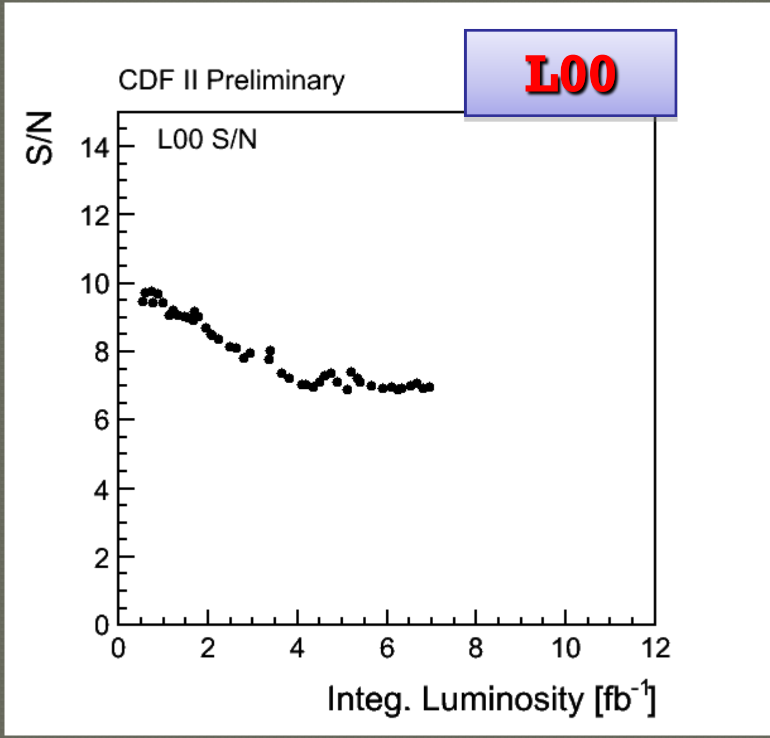
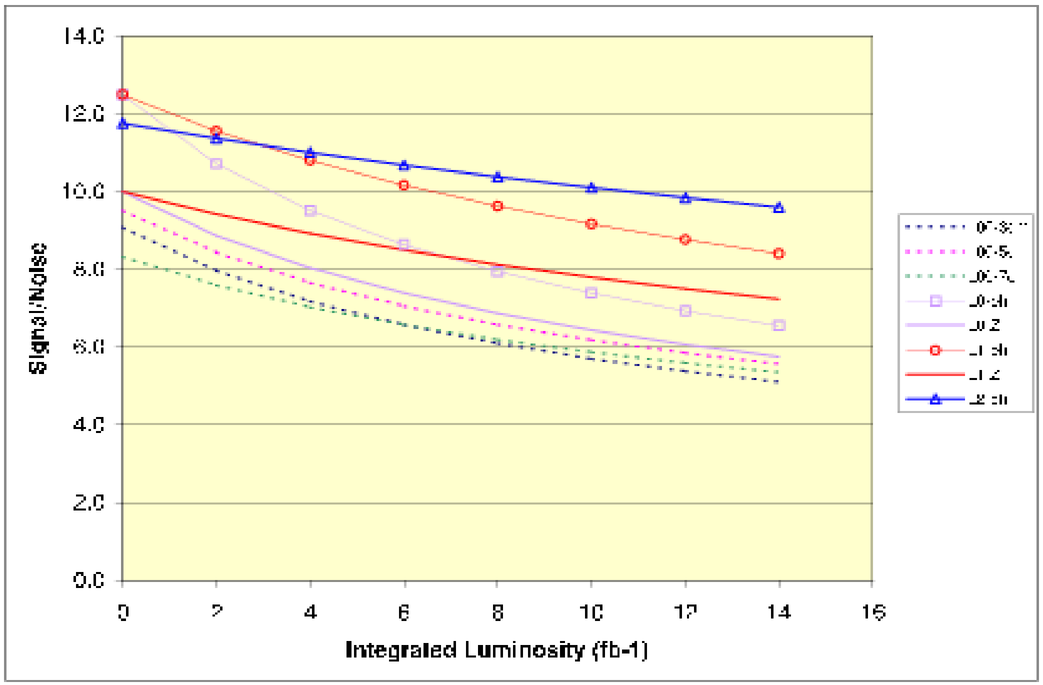
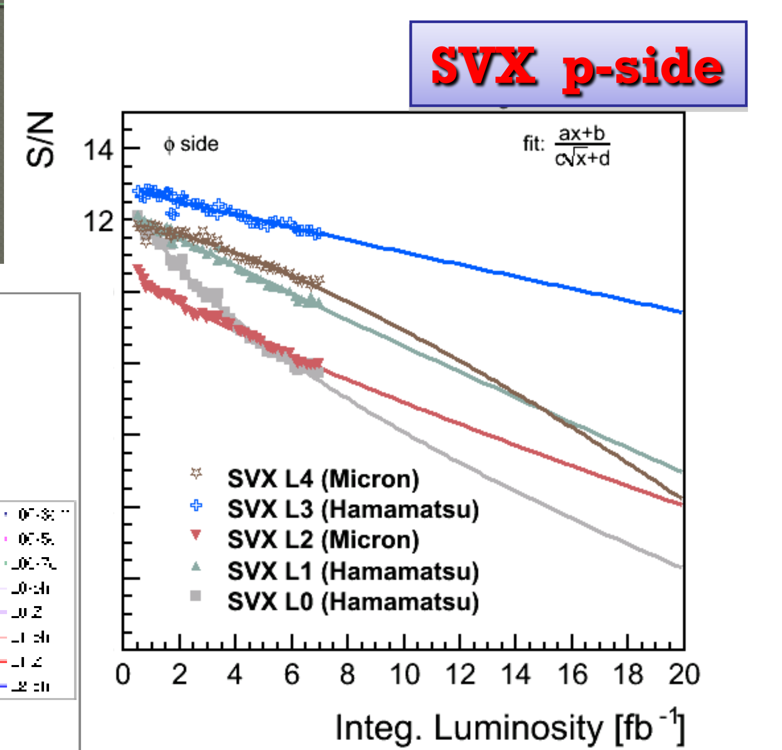




Expected S/N

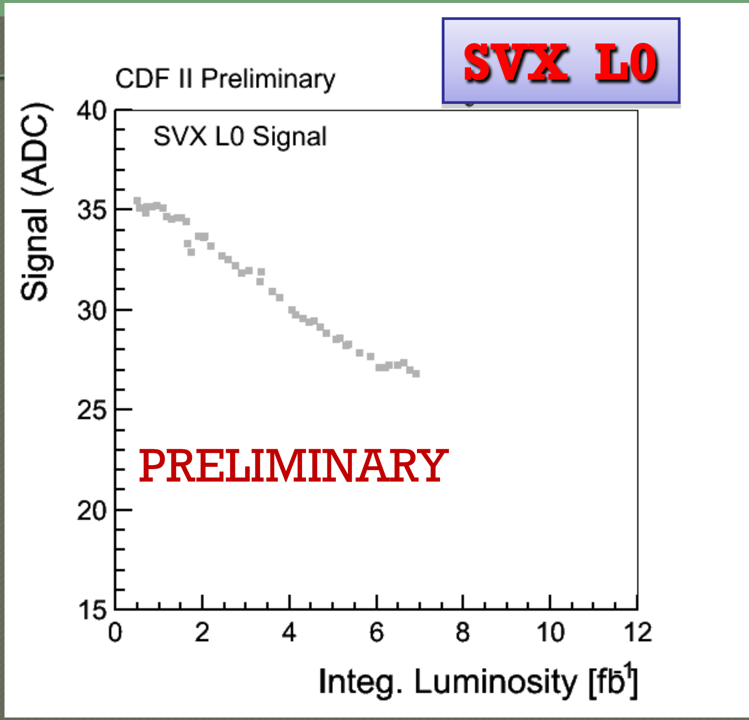
CDF note 6673 (2003) Predictions for higher coolant temperature (lowered in 2005) assumed increase in noise and no change in signal

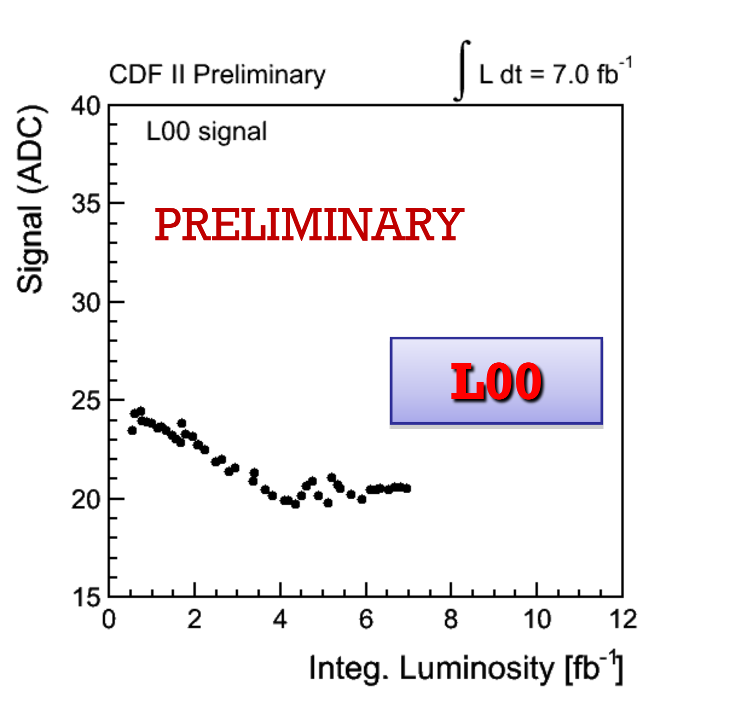




L00 (dashed lines) and SVX-L0 (grey lines) predictions roughly match data?

Unexpected signal decrease



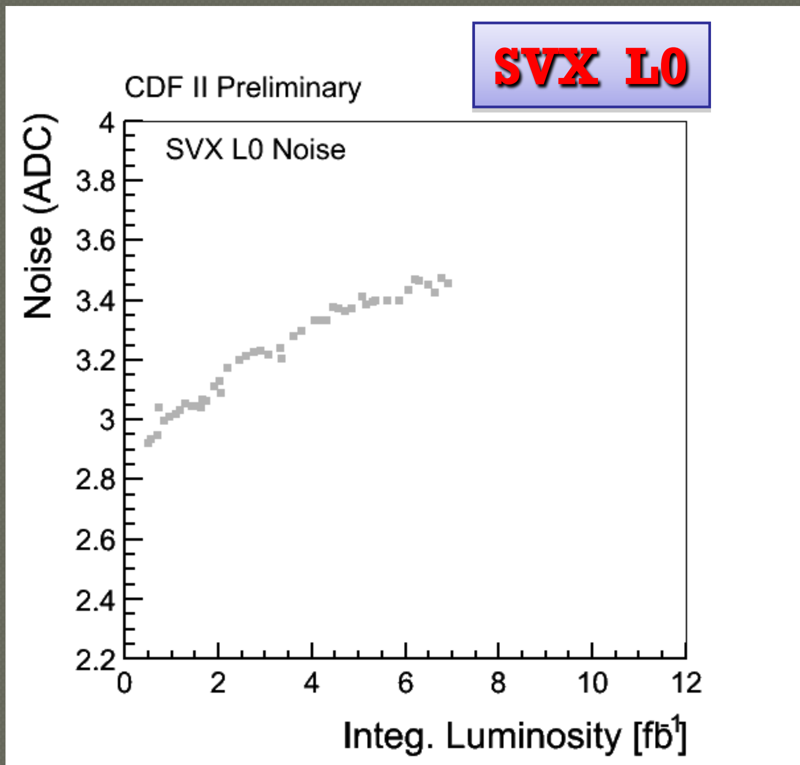


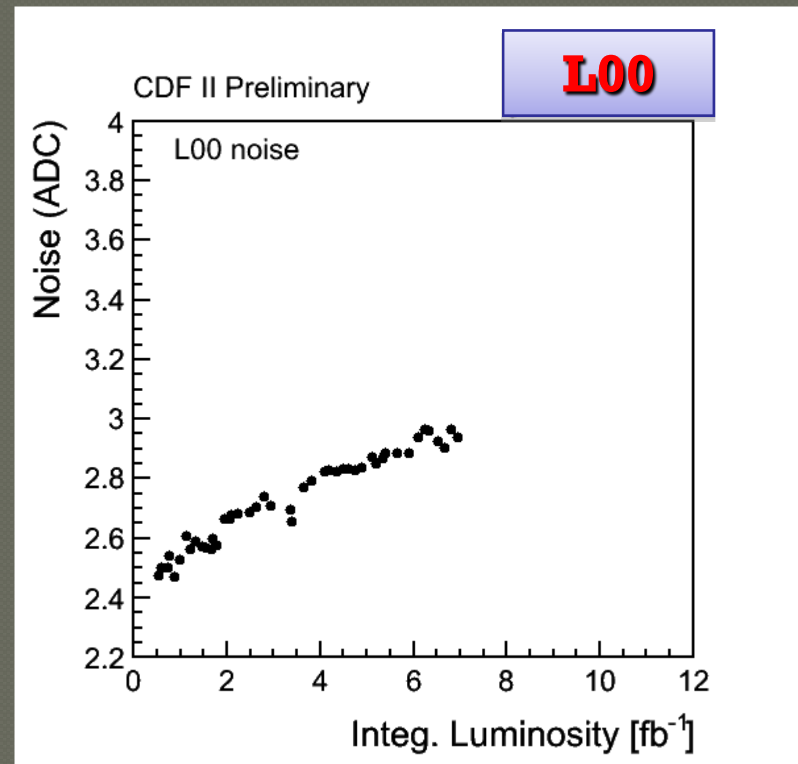
No significant decrease in the signal (total charge collected) was foreseen. CDF note #6673

Could be explained by increased charge trapping and/or slower drift velocities in the region of low electric field.

If the charge arrives at the electrode after the132 ns integration window closes, it is essentially lost.

Measured Noise

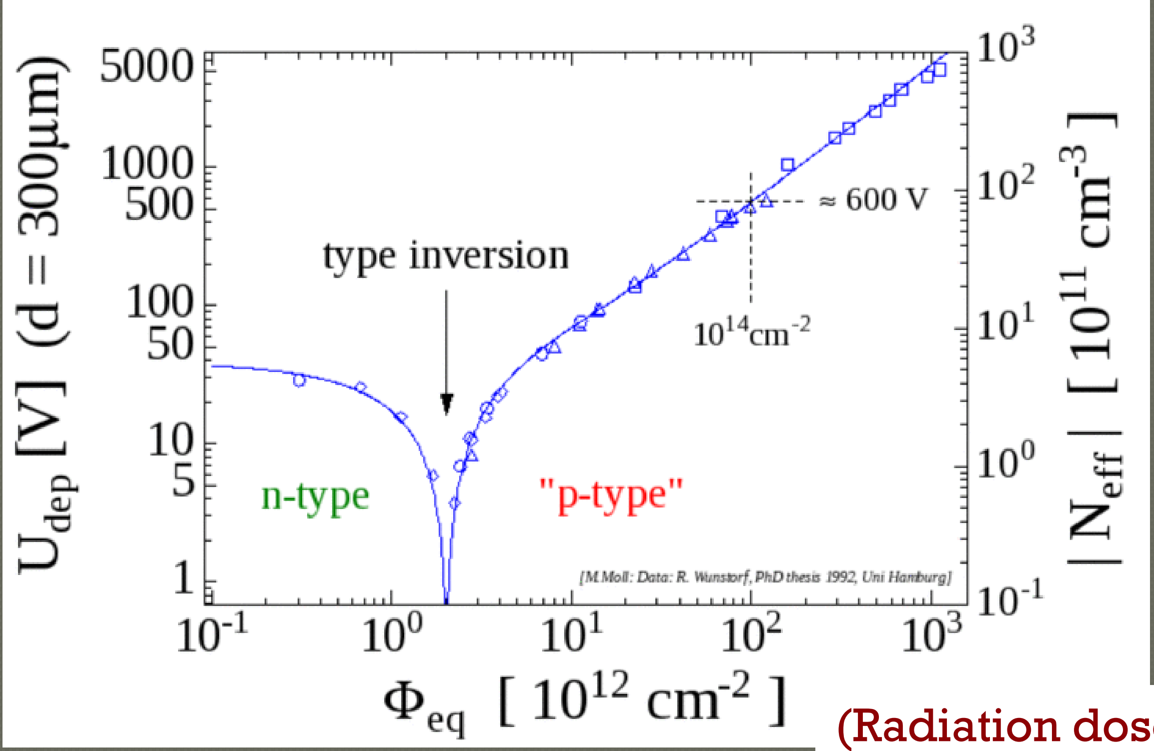




- Lower initial noise for L00 because of active cooling
- Similar trends for different radiation doses!

Depletion Voltage

Depletion voltage – minimum voltage at which the bulk is free of mobile charge carriers.



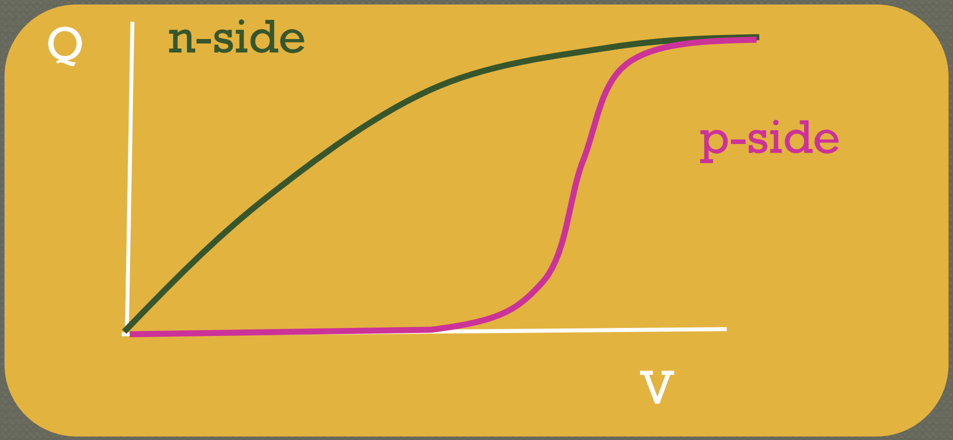
(Radiation dose)

Depletion Voltage (2)

Popular belief at time of CDF-II Construction . . .

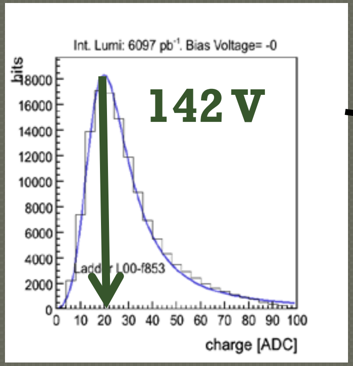
After type inversion, the sensor depletes from the n side to the p side, because the bulk has become "p-type".

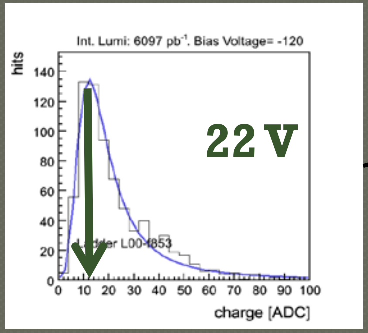
The p-side of the sensor does not work when under-depleted!

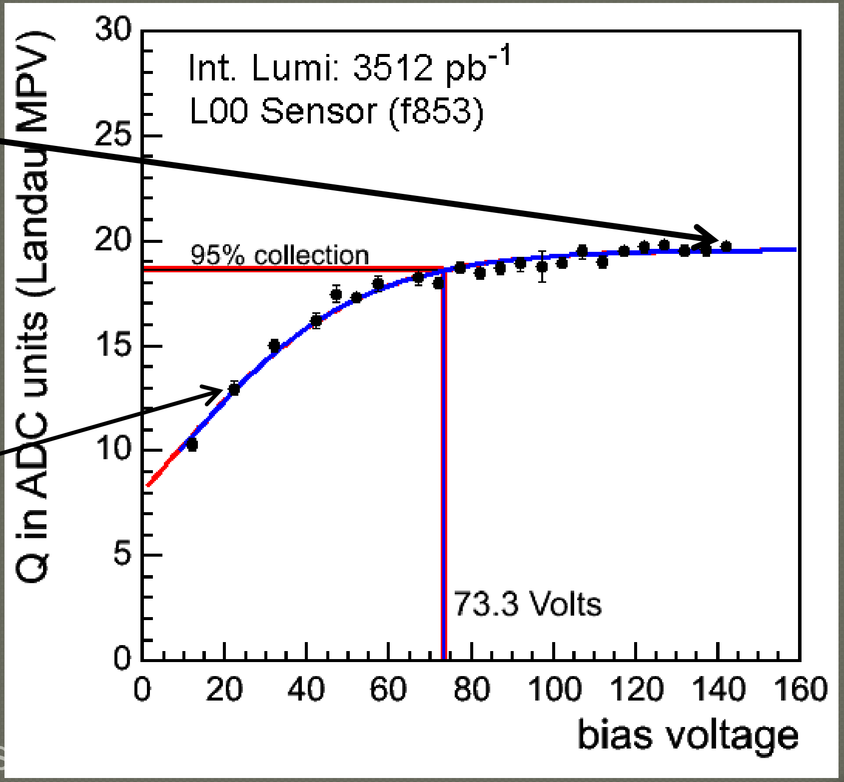


Depletion Voltage Measurement

- Plot peak charge for offline clusters as a function of bias voltage
- CDF defines depletion voltage as **the minimum voltage that collects 95% of the charge at the plateau**

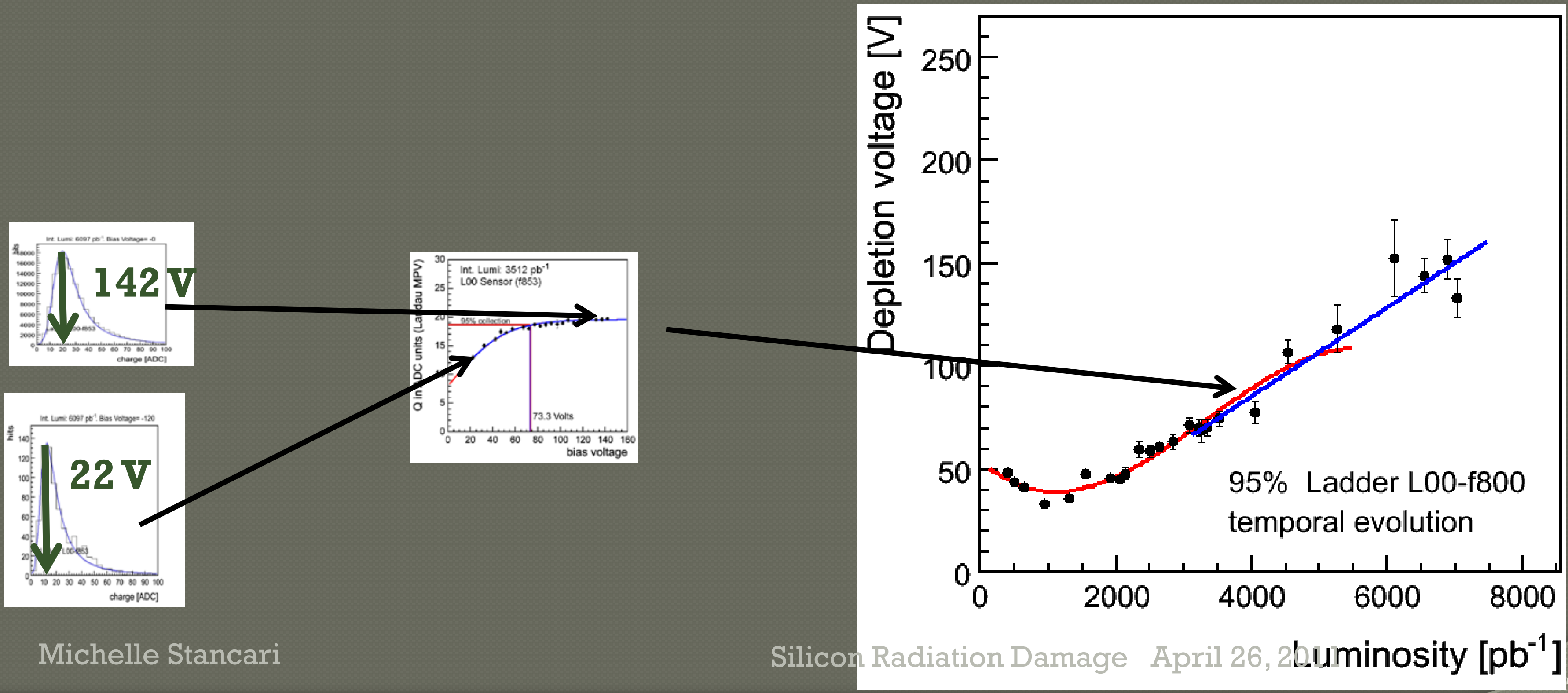






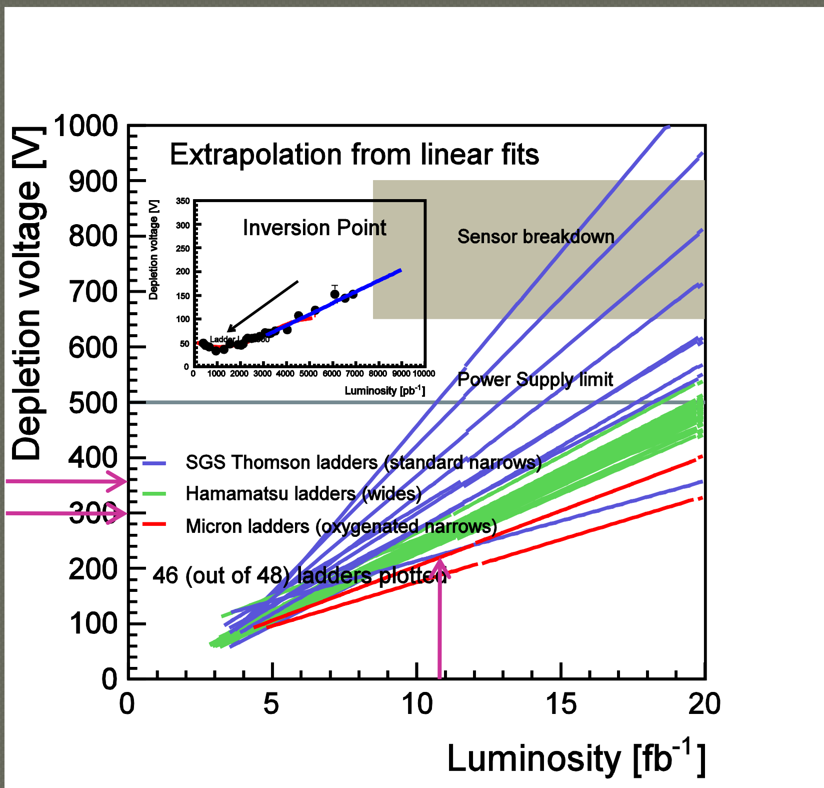
Depletion Voltage Measurement

- Plot collected charge for different bias voltages
- Determine depletion voltage as the minimum voltage that collects 95% of the charge at the plateau
- Extrapolate into the future
  - 3rd order polynomial fit around the inversion point, linear fit after



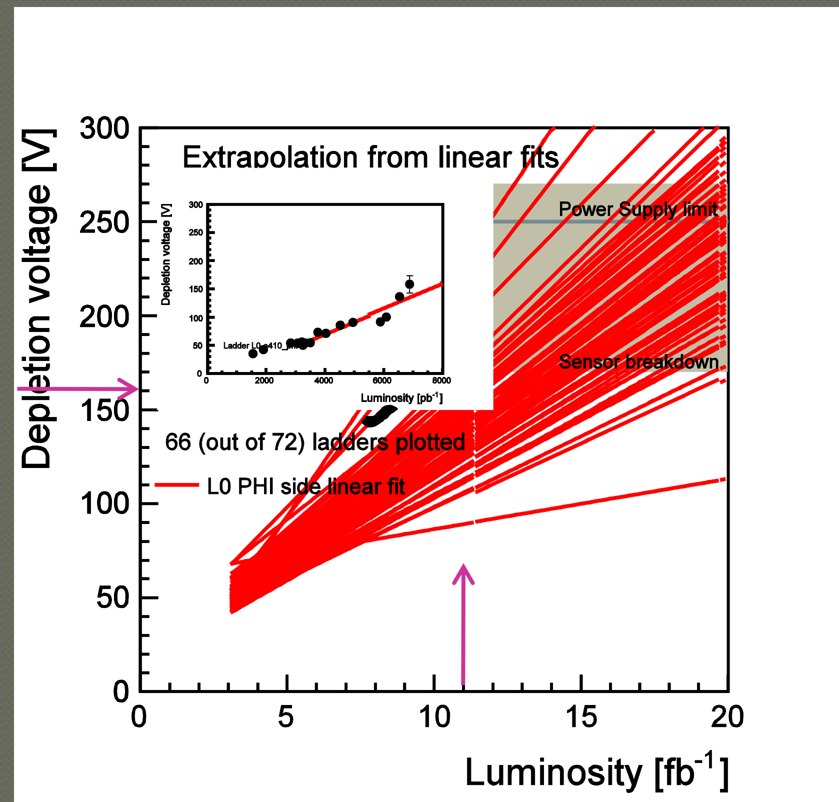
Depletion Voltage Projections

L00

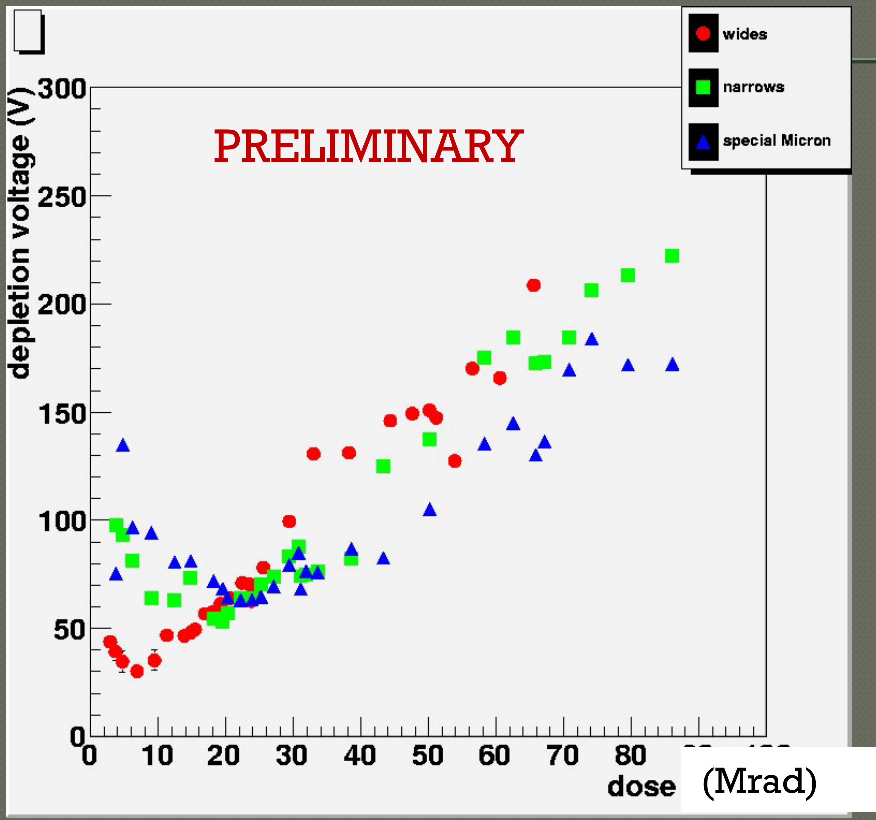


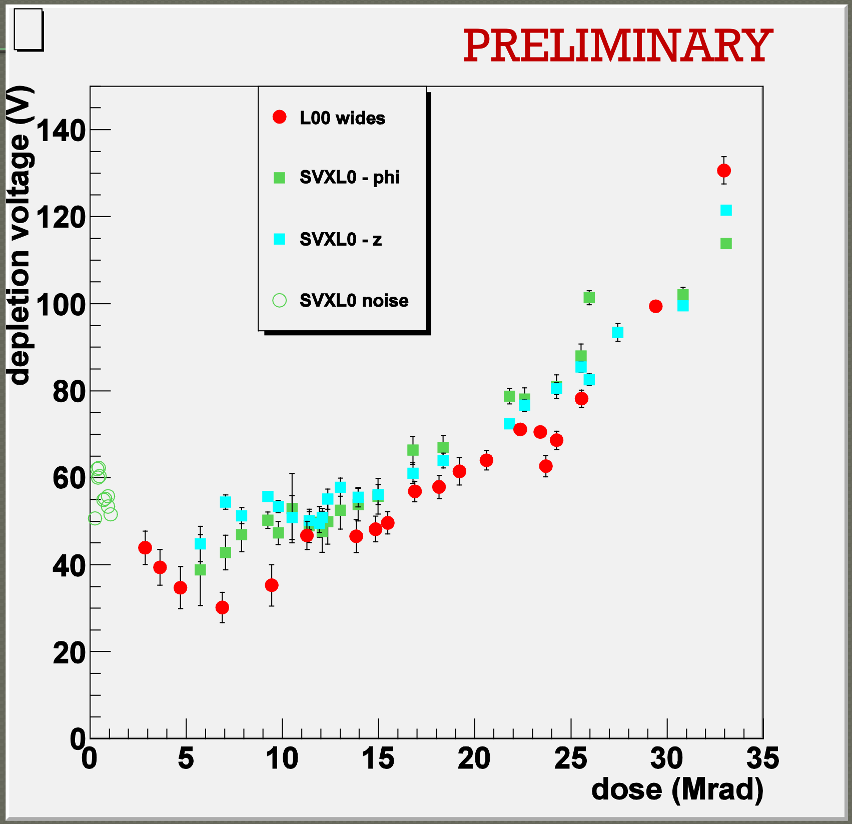
SVX-L0

Where we are now



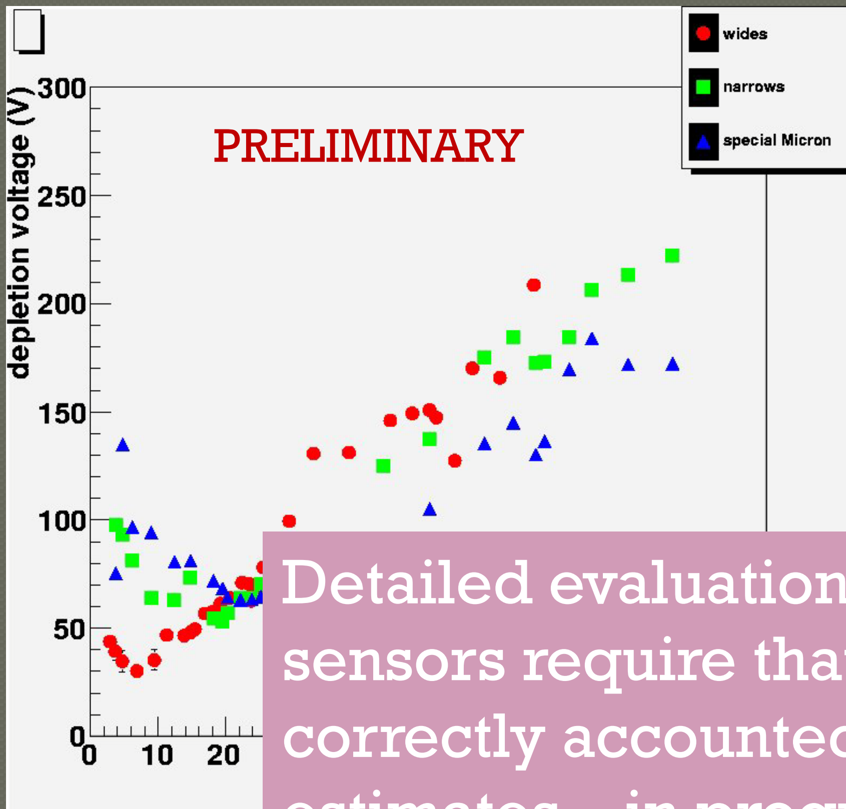
Depletion Voltage Comparison

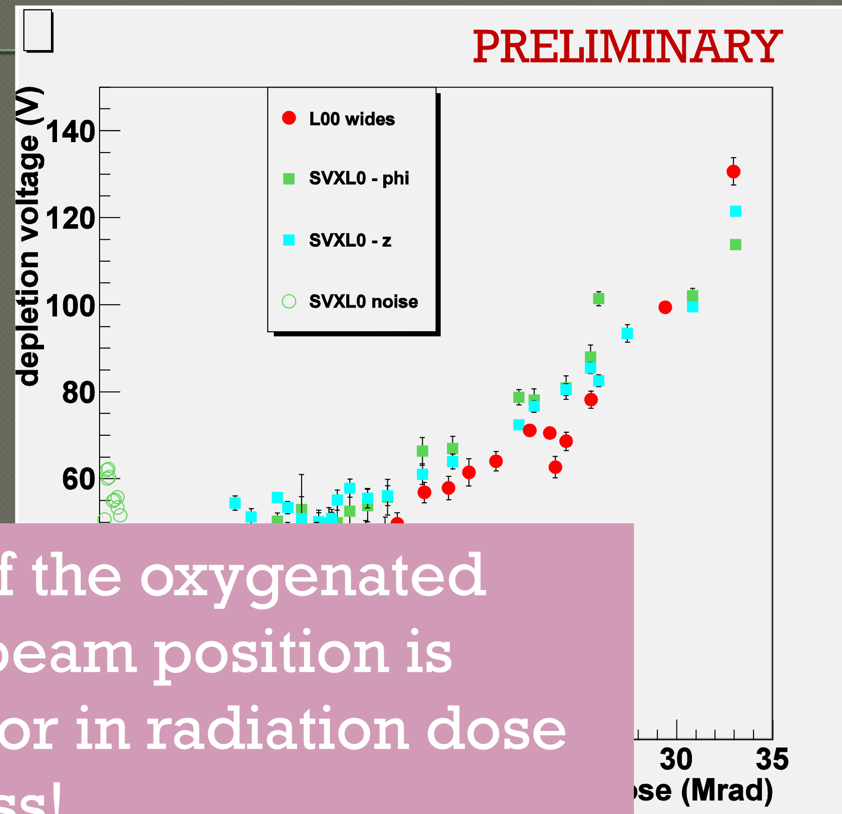




- Depletion voltage is averaged over all sensors in a layer
- Assume interaction region is at the center of the detector
- Conversion from luminosity to ionizing radiation dose using TLD measurement of CDF radiation field NIM **A514** (2003) 188.

Depletion Voltage Comparison



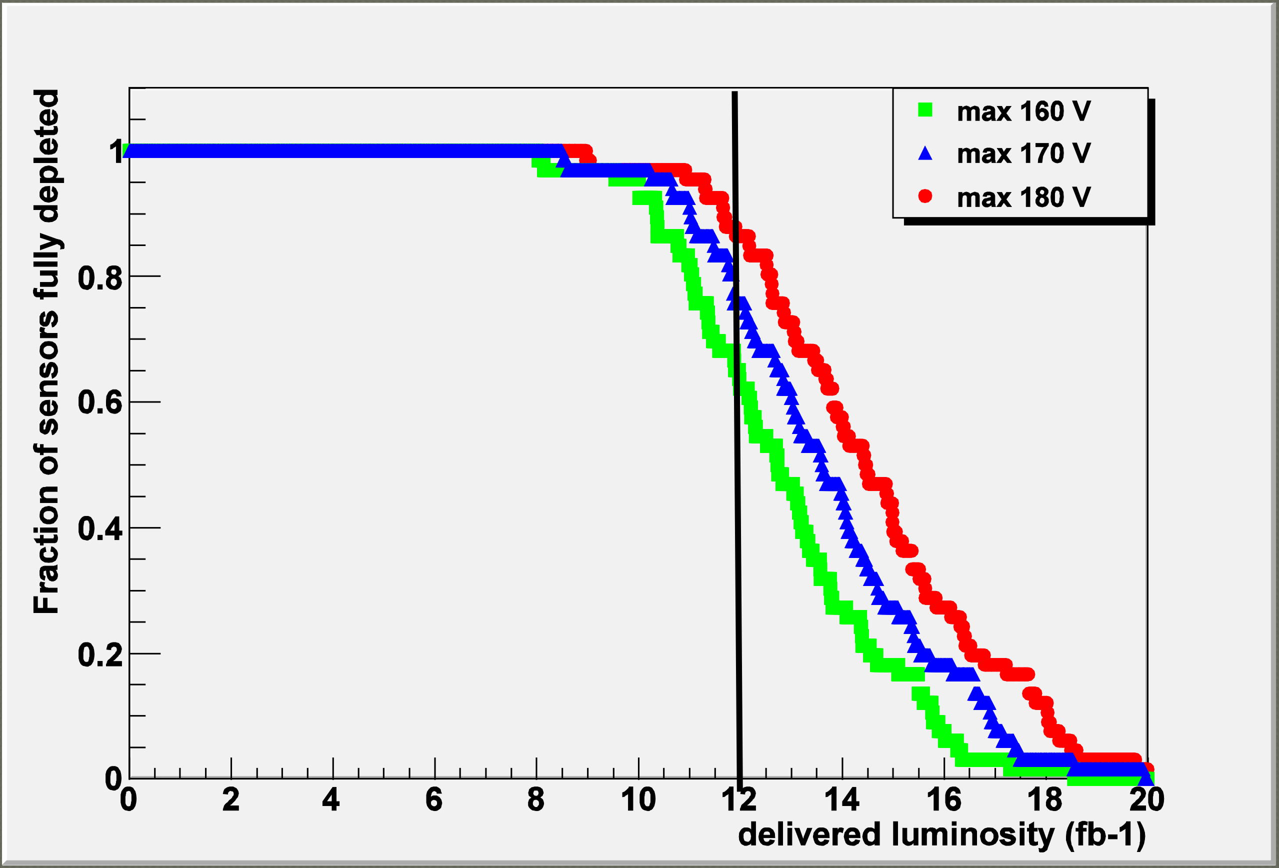


Detailed evaluation of the oxygenated sensors require that beam position is correctly accounted for in radiation dose estimates – in progress!

- Depletio
- Assume interaction region is at the center of the detector
- Conversion from luminosity to ionizing radiation dose using TLD measurement of CDF radiation field NIM **A514** (2003) 188.

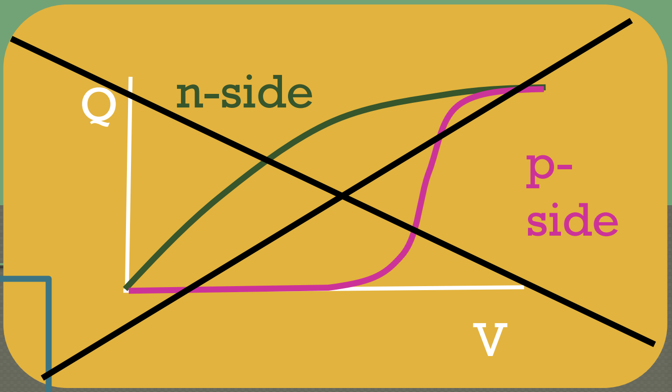
SVX-L0 prognosis for 12 fb^{-1}

- All ladders at 160 V currently
- Breakdown voltage is uncertain
  170-200V
- At 160V, loss of efficiency expected for only 3 of 72 ladders

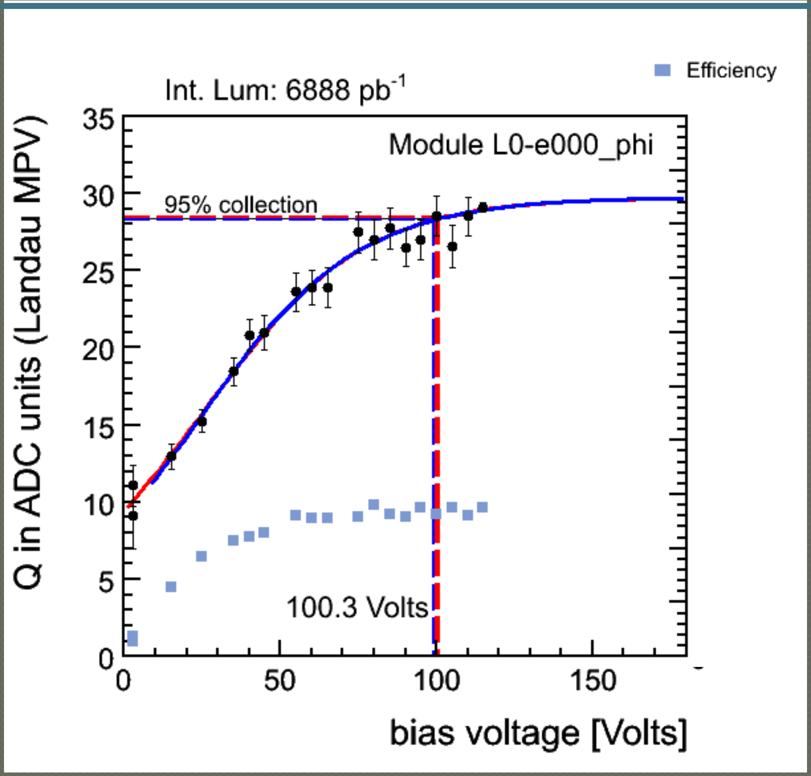


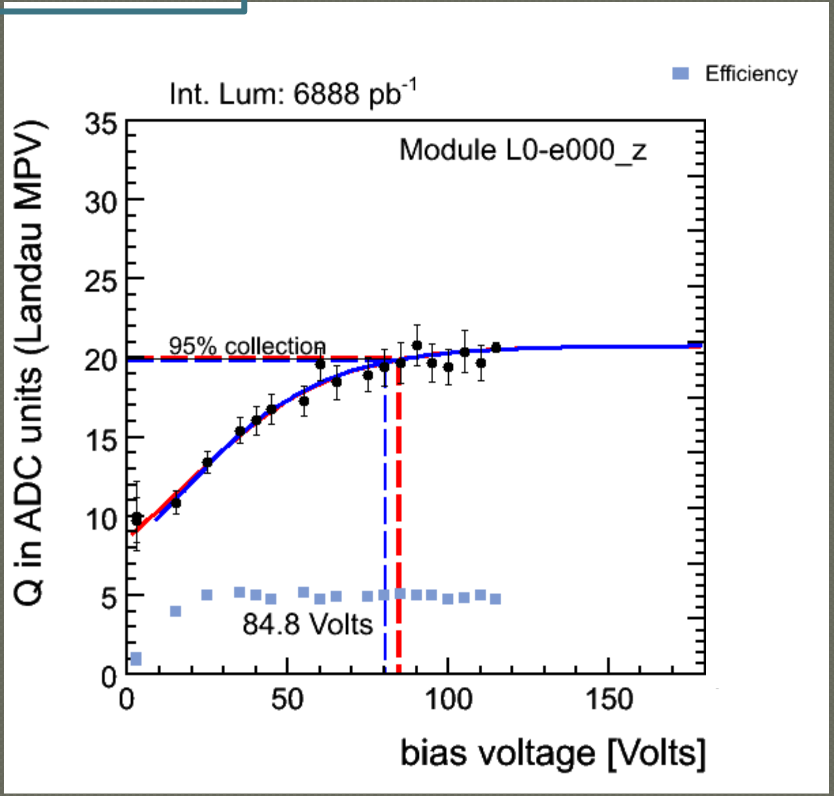
*updated data analysis , may not match previous slides exactly

Surprise!

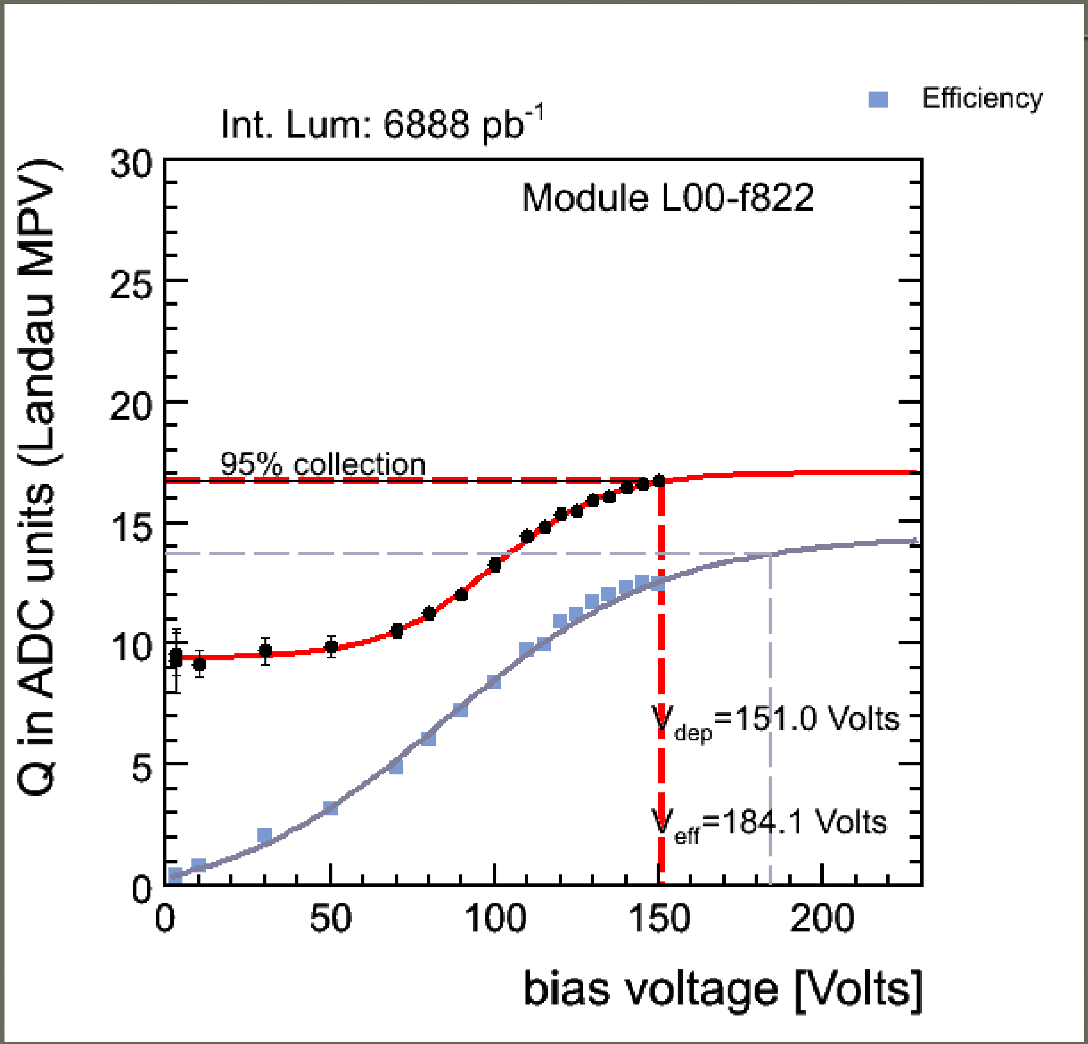


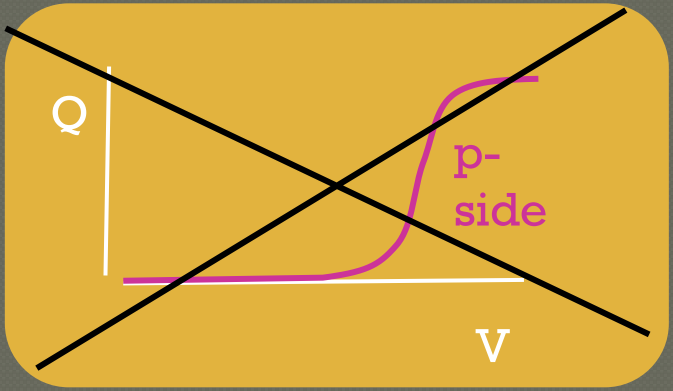
Underdepletion is NOT instant death for the p-side! Instead, a slow process of decreasing efficiency.





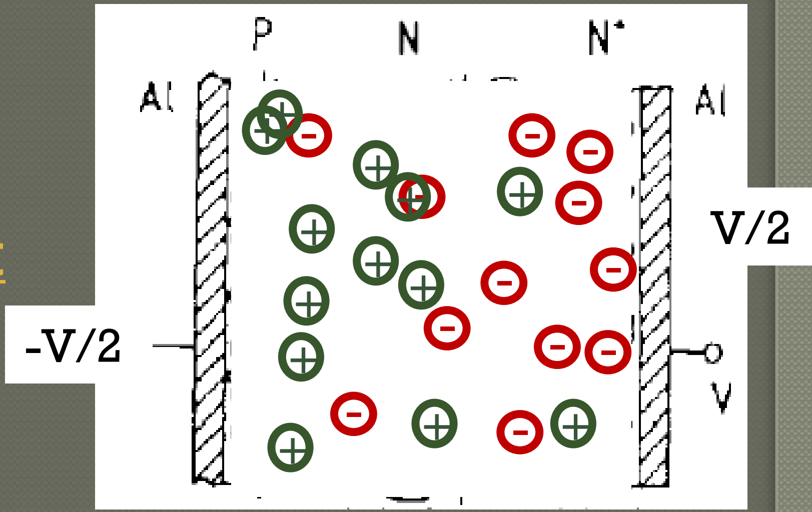
L00

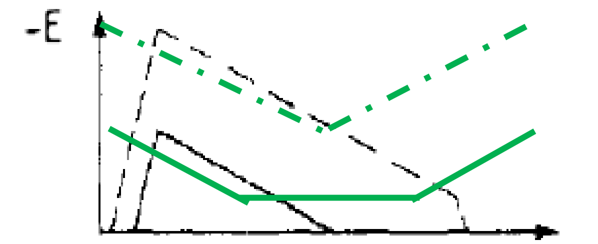

Efficiency
Int. Lum: 6888 pb-1
Module L00-f822
95% collection
Q in ADC units (Landau MPV)
30
25
20
15
10
5
0
0
50
100
150
200
Vdep=151.0 Volts
Veff=184.1 Volts
bias voltage [Volts]


Q
p-
side
V

Double Junction Model

- Radiation damage creates crystal defects which trap free charge
- Not only is charge from MIPs trapped, but also holes and electrons from the bias current
- Space charge distribution develops in the bulk
- Resulting electric field is large at the sensor edges and small in the center
- The center of the sensor is the last part of the bulk to get depleted.





Beam tests of LHC-type sensors

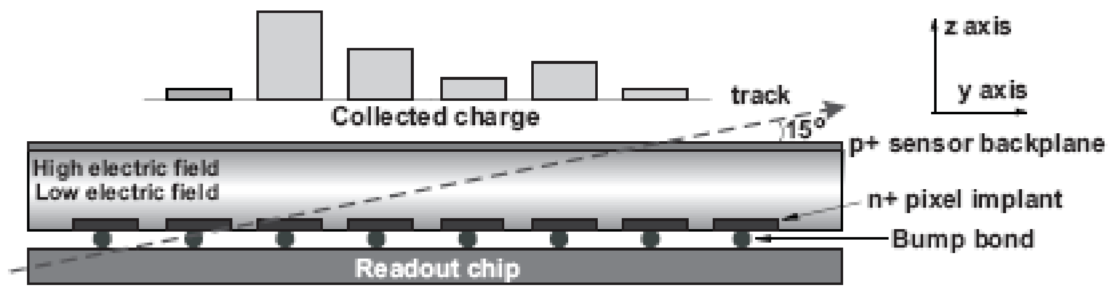


Fig. 2. The grazing angle technique for determining charge collection profiles. The charge measured by each pixel along the y direction samples a different depth z in the sensor.

NIMA 565 p 212 (2006) or physics.ins-det/0510040v2

- Double Junction model developed that predicts the observed behavior. (Evolution of trap concentrations with fluence.)
- Would the same model tuning predict our observations?
- Conversation has begun . . . . . .

Summary and Conclusions

Efforts to reduce S/N loss in L00 were successful!

Tevatron data offer unique measurements of radiation damage in silicon detectors

Our heavily irradiated sensors are behaving differently than expected:

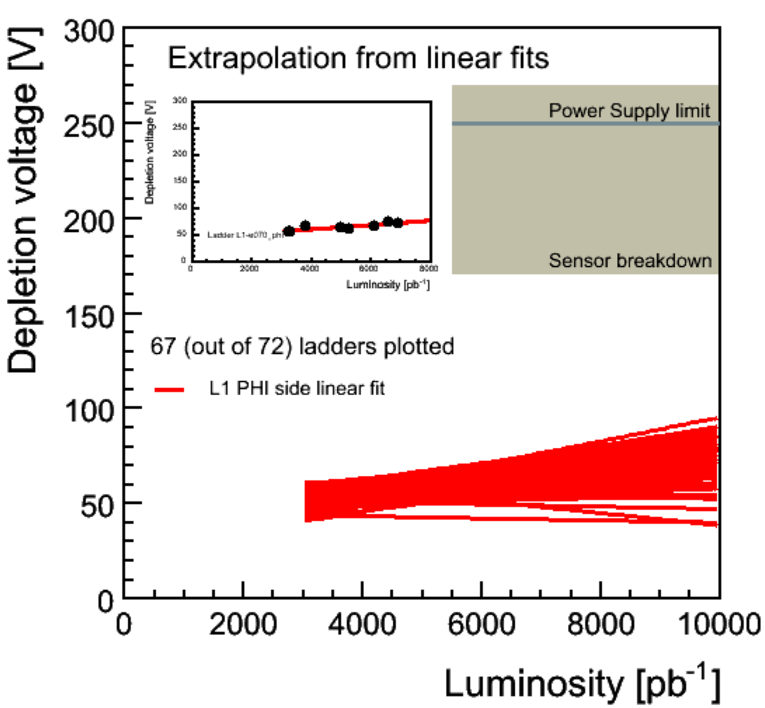
- The S/N predictions for the CDF detector differ from the measured data.
- Slightly underdepleted sensors still give good data on both sides of the sensor.

Qualitative confirmation of new double junction model

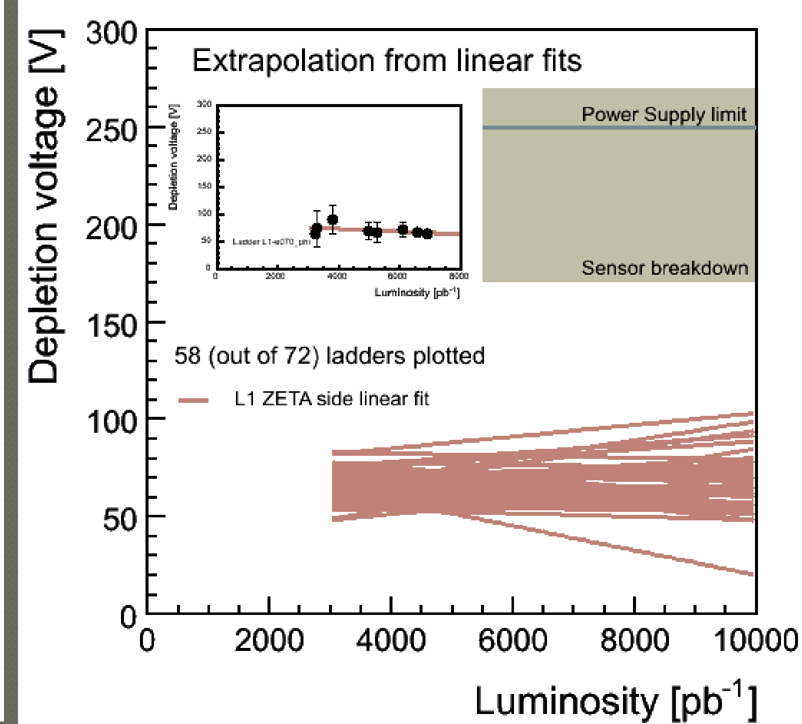
Backup Slides

Depletion Voltage Projections

Prediction for L1 – phi side



Prediction for L1 – z side



Michelle Stancari
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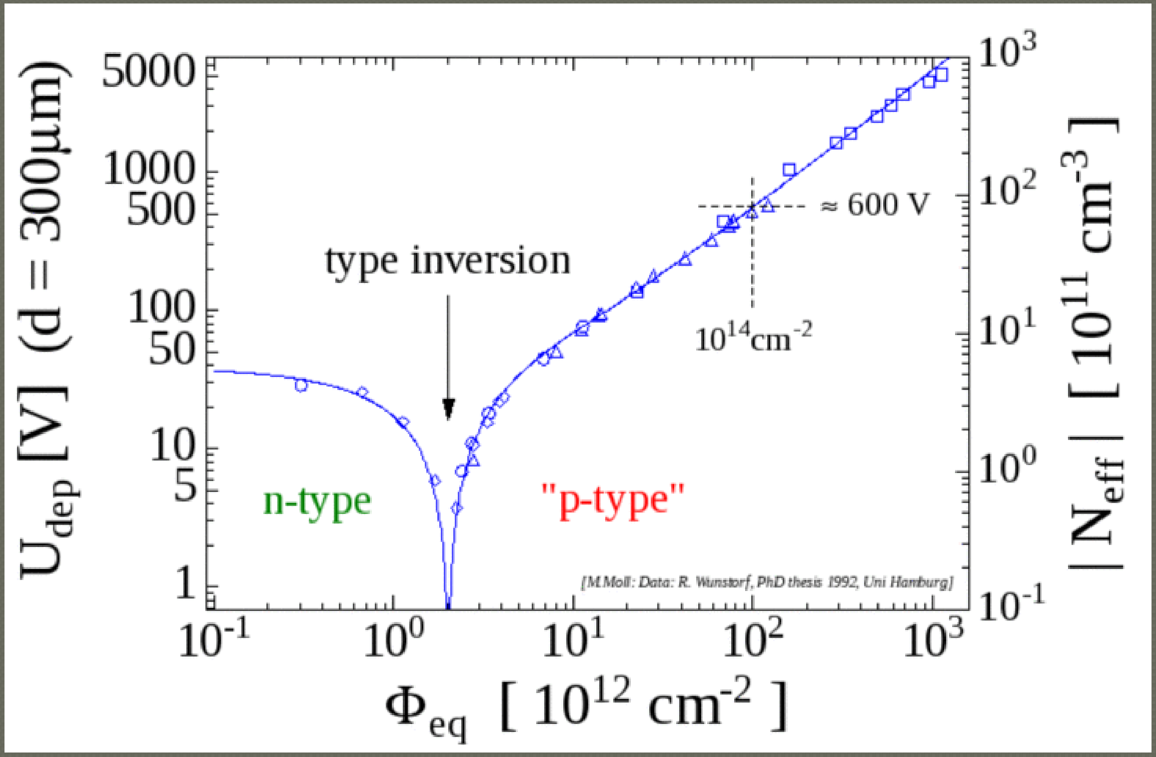
Depletion Voltage

The depletion voltage changes with radiation dose. The Hamburg Model parameterizes this as a change in the effective doping concentration

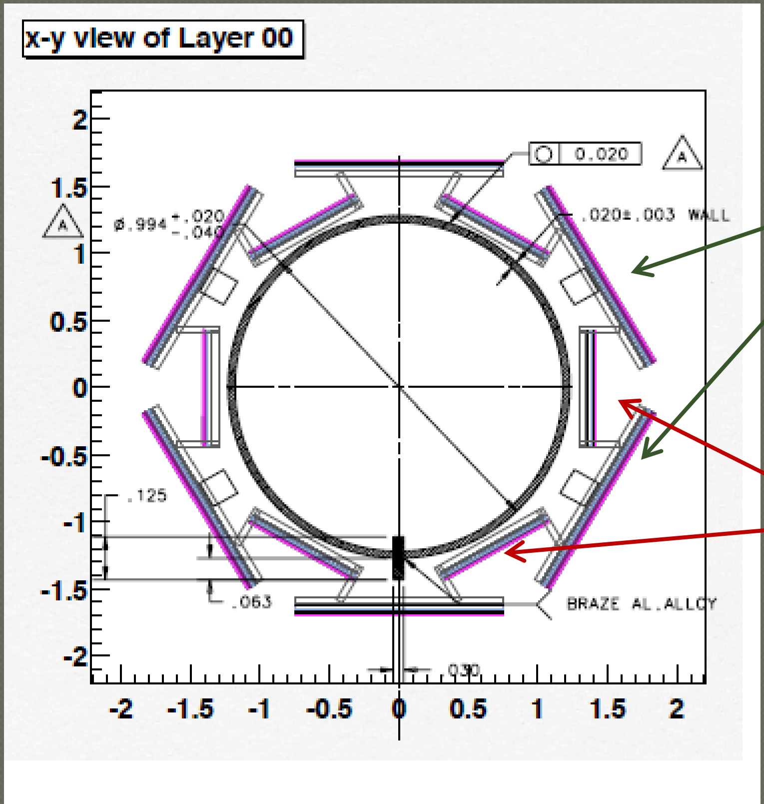


$$U_{dep} = \frac{qND^2}{2\varepsilon}$$

D=sensor thickness
ε=dielectric constant of silicon
N_{eff}=doping concentration of bulk
q=elementary charge in the depleted region
ρ=1/Nμq resistivity
μ = charge carrier mobility

Equation from Moser "Progress in Particle and Nuclear Physics" **63** (2009) 186-237

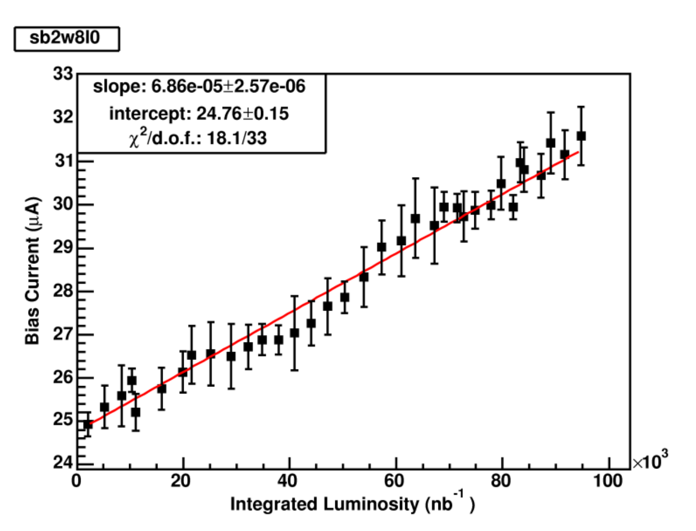
L00 geometry

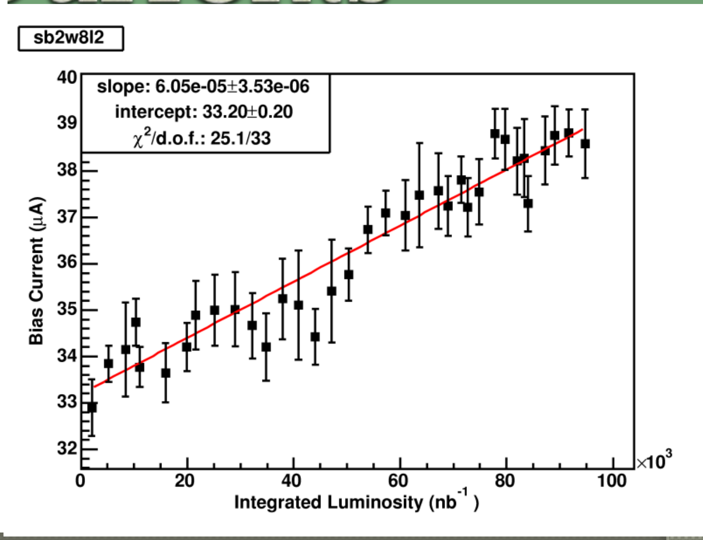


"Wides" at r=1.62 cm made by Hamamatsu

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

Evolution of Bias Currents

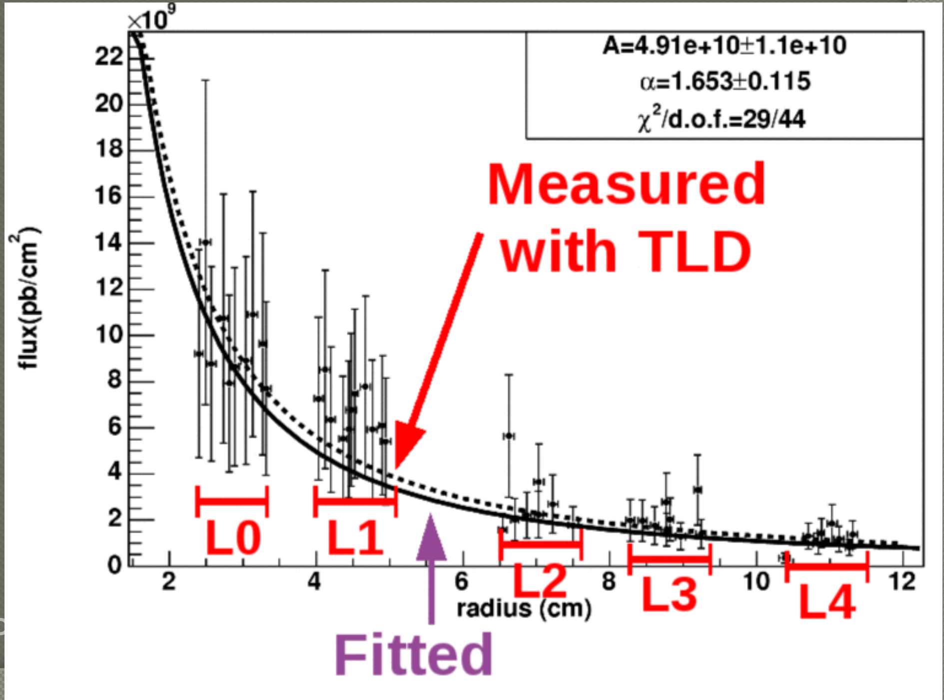




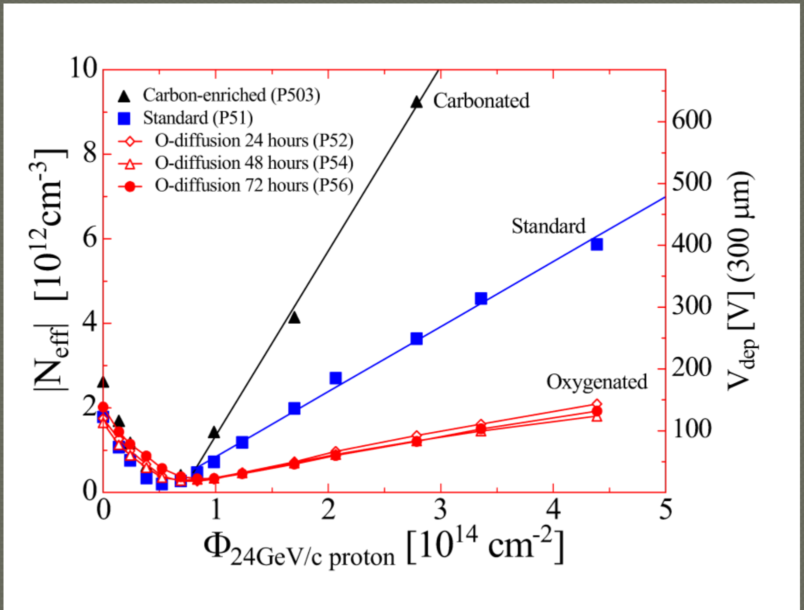
- α_{dam} is constant for several orders of fluence
- The **fluence – integrated luminosity relationship** depends on distance of the sensor to the beam

$$\phi = Ar^{-\alpha}$$

- Using a 95 pb^{-1} data sample, a damage factor of **(4.47 ± 0.14) x 10^{-17} A/cm** was extracted (P. Dong et al. CDF/8219).

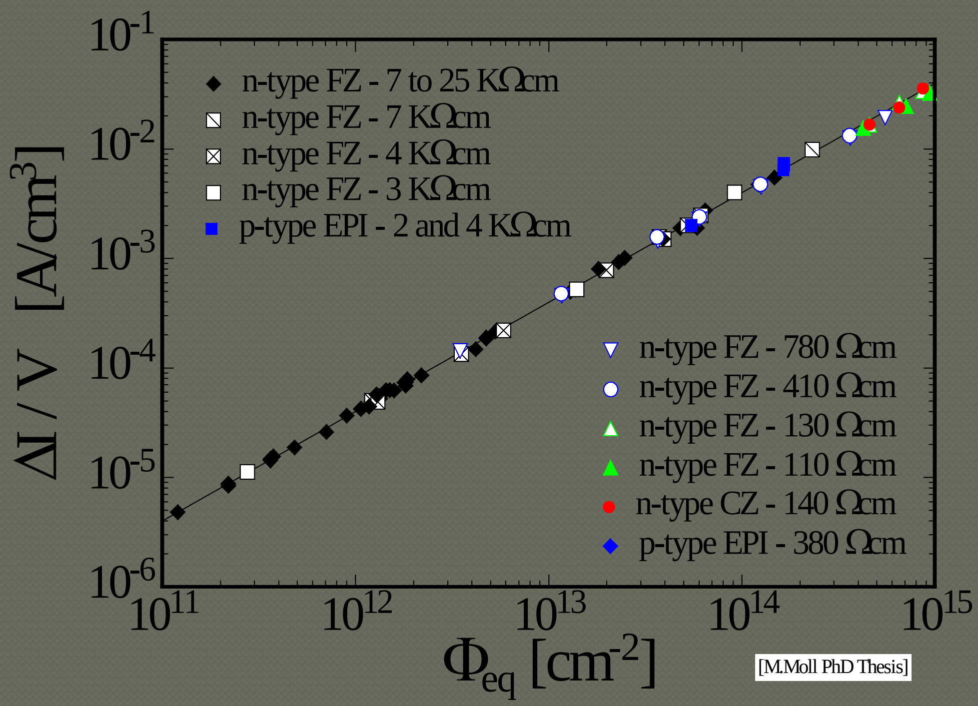


Oxygenated Sensors



A.Ruzin et al., Nucl. Instr. And Meth. A 447 (2000) 116

Damage constant



- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current
per unit volume
and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement