CDF Run-II Silicon Detector: Operation and Aging

Michelle Stancari
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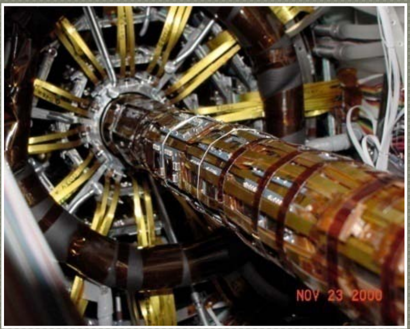
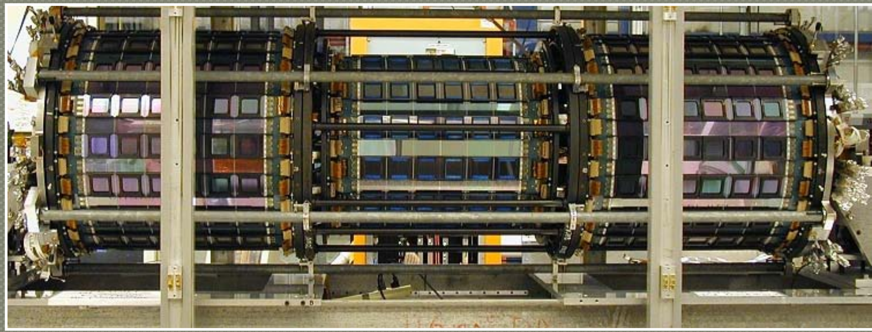
(on behalf of the CDF-II Silicon group)





Vertex2011
Rust, Austria | 19–24 June 2011

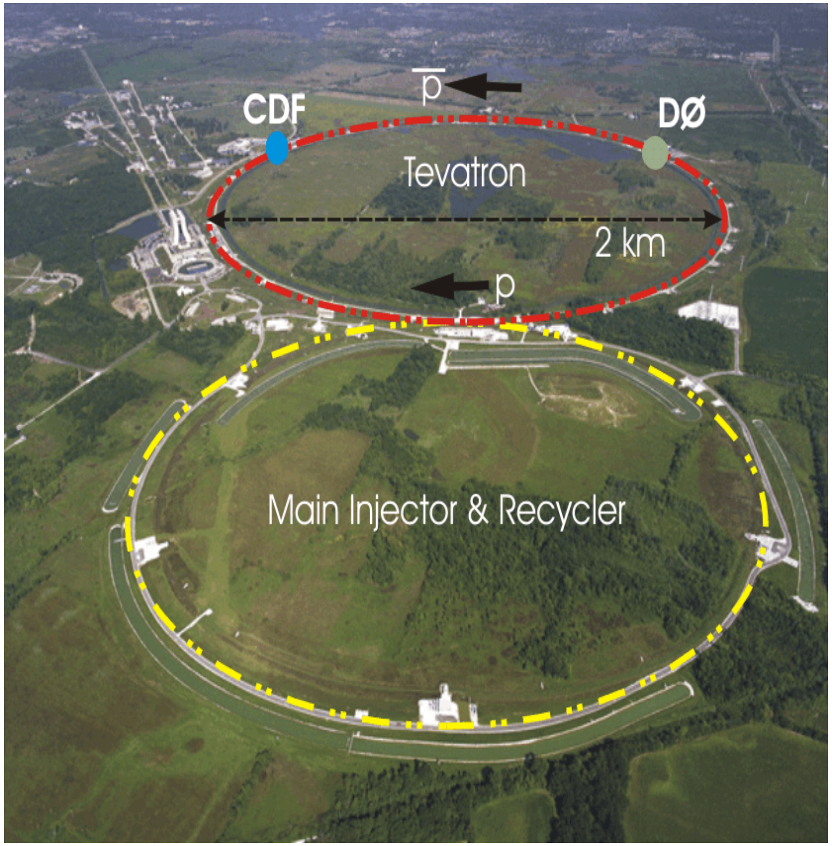
Outline

- Introduction and Detector Description
- Current status
- Operation Challenges Past and Present
- Aging Studies
  - S/N measurements
  - Depletion Voltage measurements
  - "Experimental" oxygenated sensors
  - Double Junction Model
- Future Plans

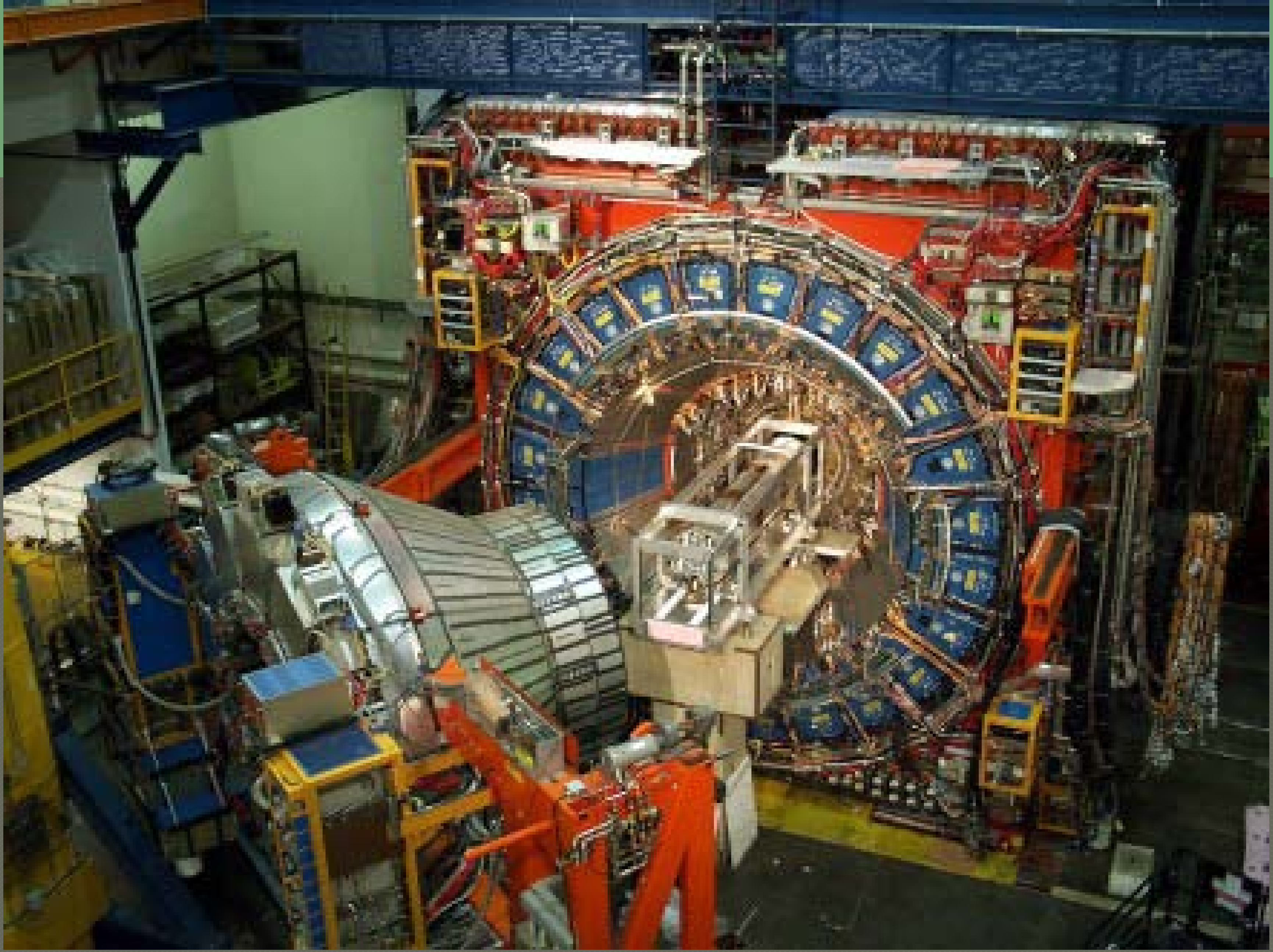
Introduction

It takes an army . . .

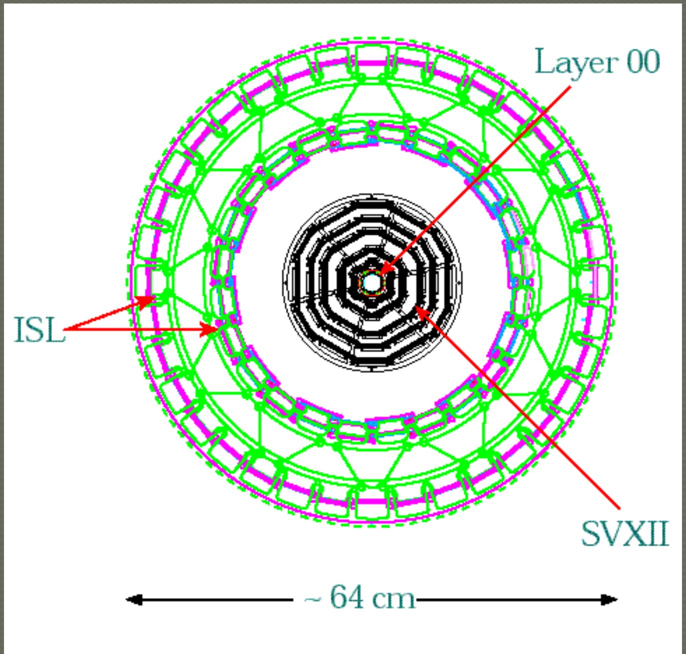
The Tevatron – 25+ years

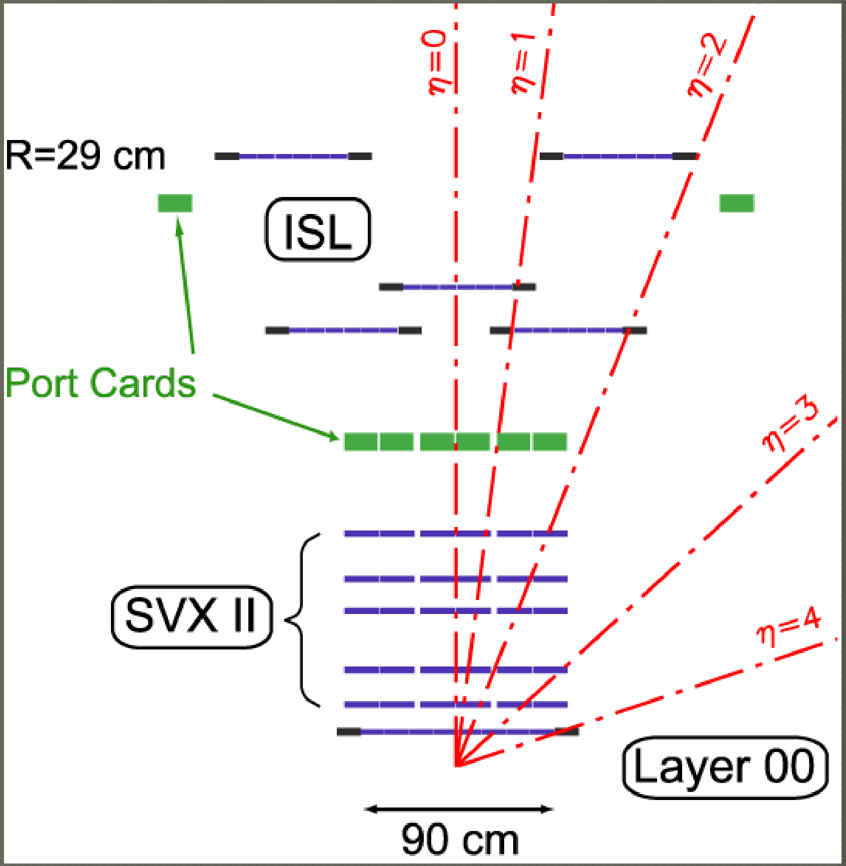


- proton-antiproton collider at $\sqrt{s}$ = 1.96 TeV
- Two multi-purpose detectors: CDF & DØ
- ~55 pb^{-1}/week, ~2.5 fb^{-1}/year
- Antiproton Accumulation rate:
  ~25x10^{+10} (hr^{-1})
- Initial luminosity record:
  4.31 x10^{32} cm^{-2} s^{-1} (May 3, 2011)
- Record week: 85 pb^{-1}
- Run II: 2001-2011
  (ends Sept 30, we expect . .)
  12 fb^{-1} delivered
  10 fb^{-1} recorded



CDF-II Silicon Strip Detectors

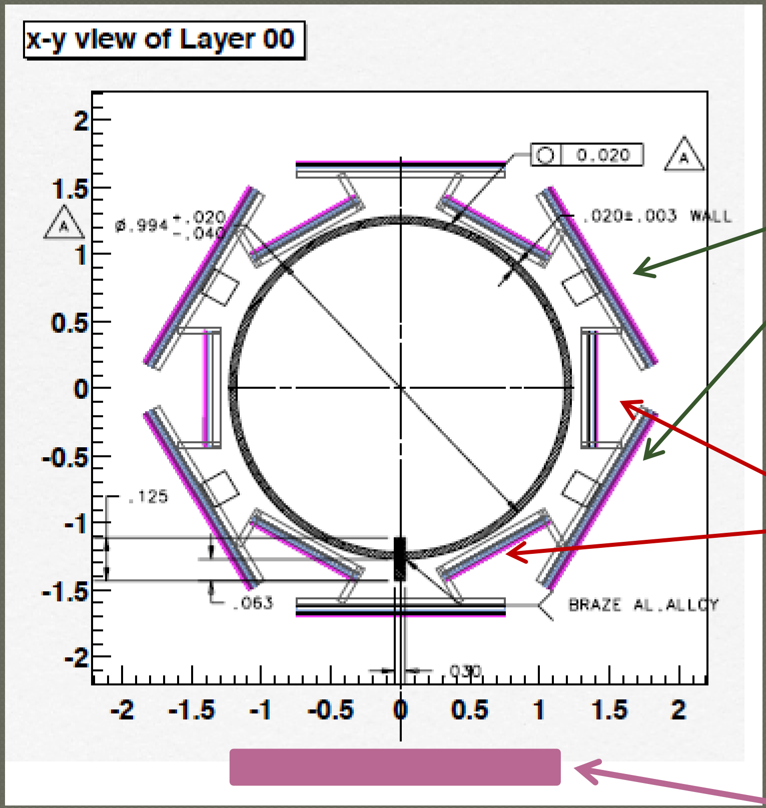




8 Layers, 704 ladders, 722432 Channels

- Layer 00 (L00): 1 Single Sided Layer
- SVXII: 5 Double Sided Layers
- ISL: 2 Double Sided Layers

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

Sensor Comparison

L00

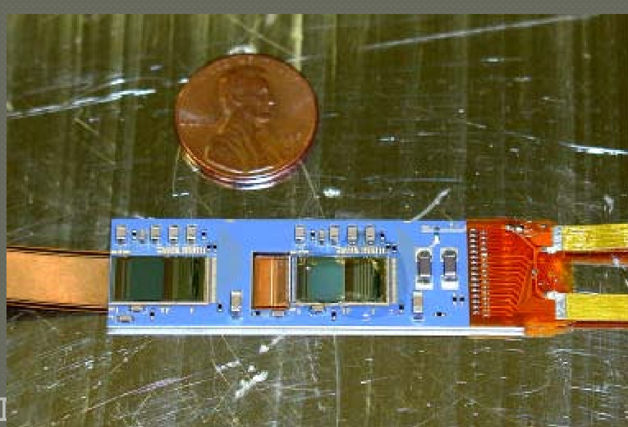
- p+ strips on n bulk single-sided
- <100>-orientation
- Sensor breakdown >600 V Power supplies <500 V
- Actively cooled sensors (-12 °C)
- Hybrids outside tracking volume
- Read out all channels each event

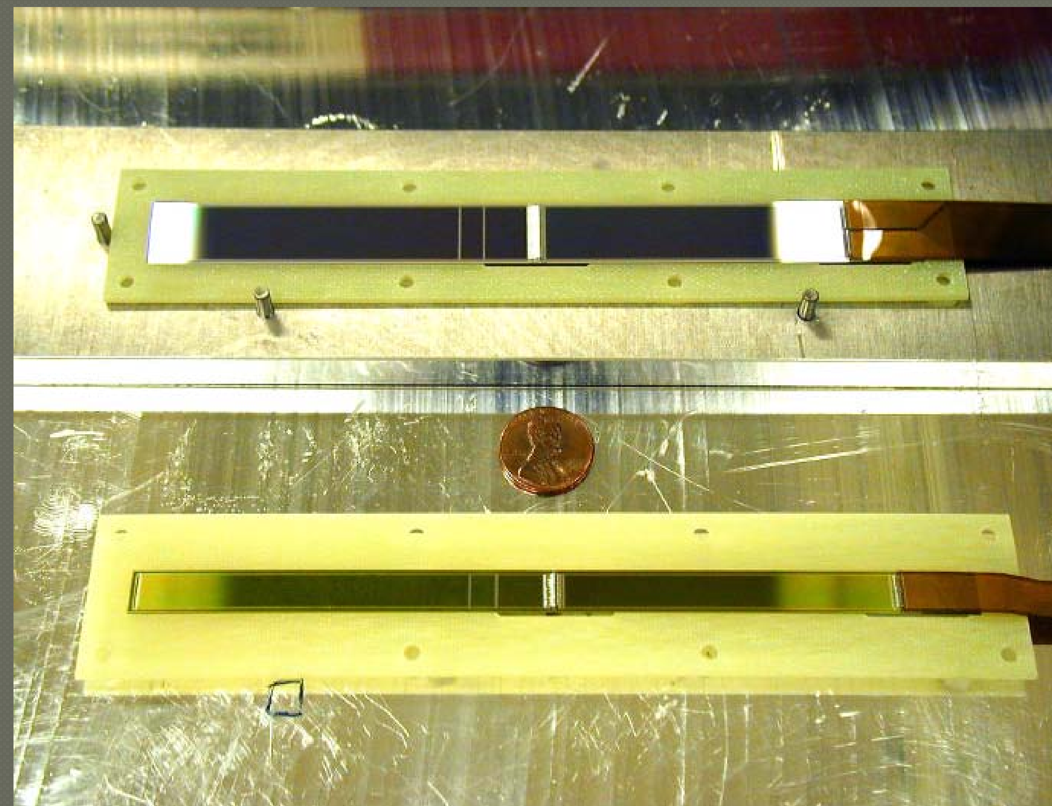
SVX

- 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

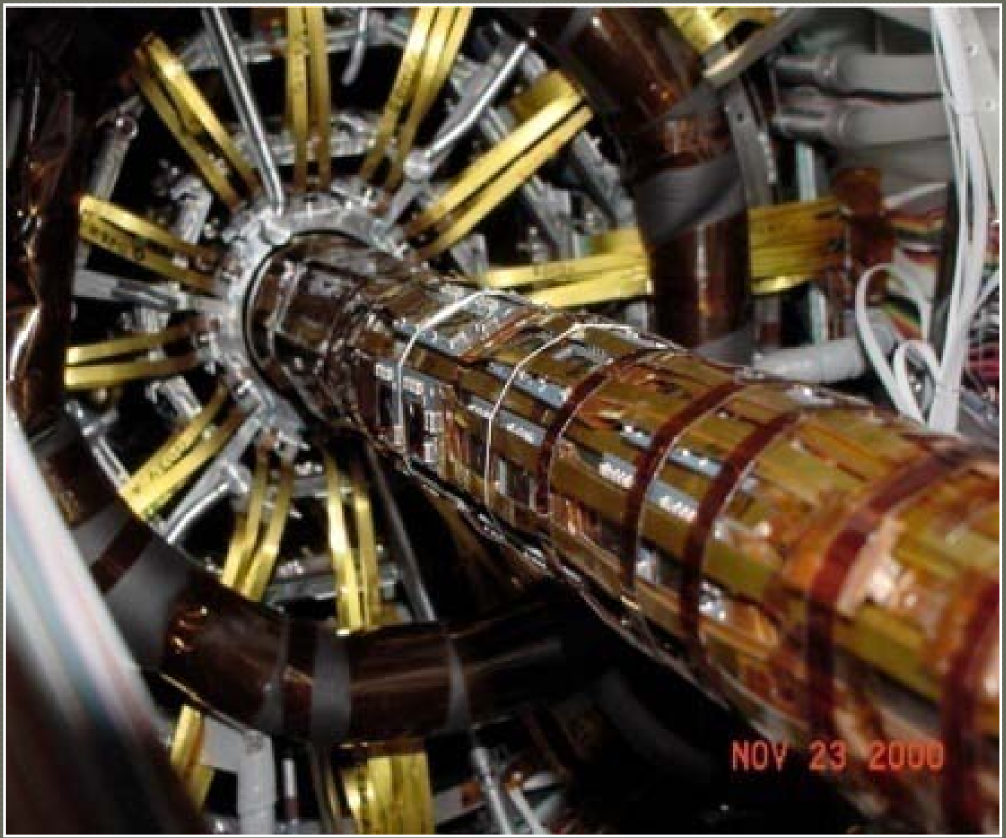
L00 designed to outlast SVX-L0 however bulk properties are the same!

L00 photo album



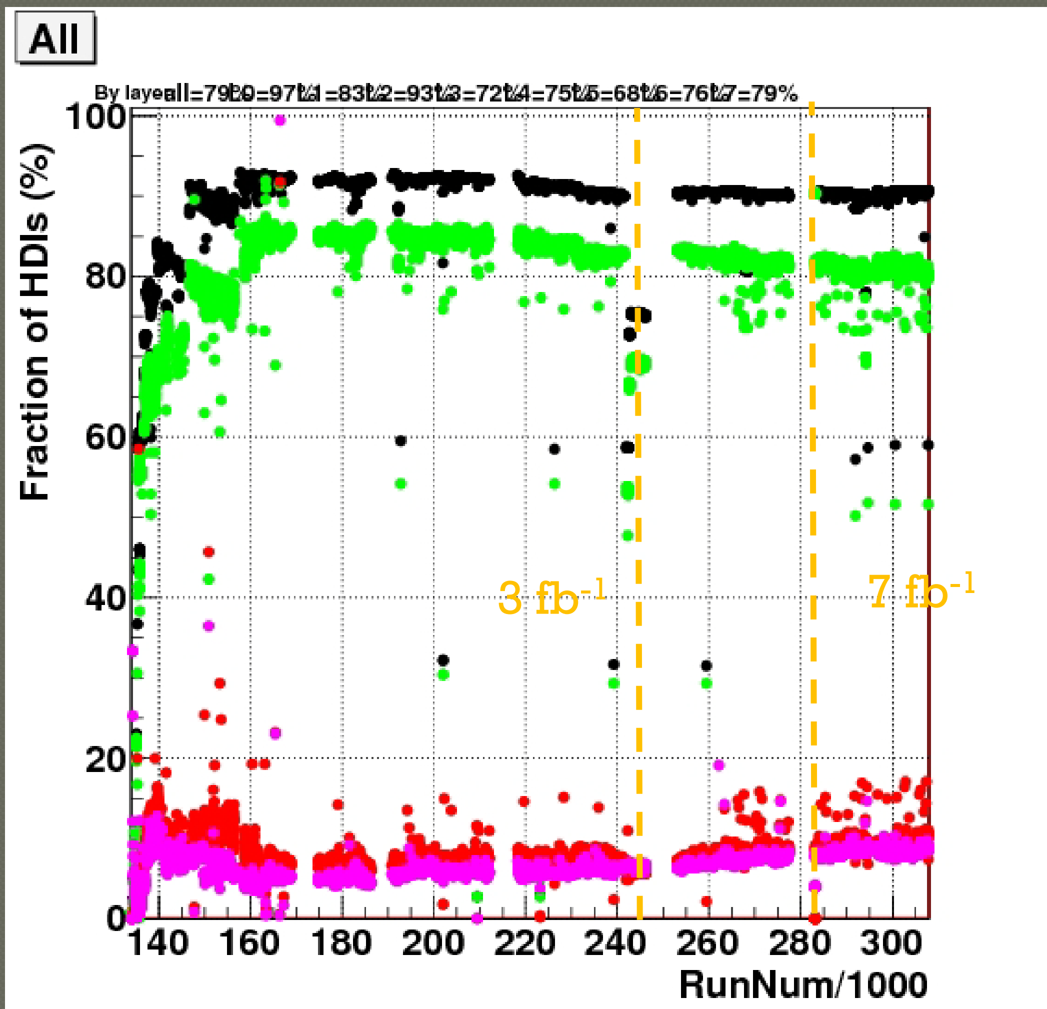


L00 and SVX



Current Status

No ladder left behind!



We use almost every opportunity for diagnostic and repair work.

~90% ladders integrated,

~80% good (< 1% error rate)

~10% bad with an average error rate of 10%

Great performance after 10 years of running

Chip Accounting - SVX

Common failure modes:

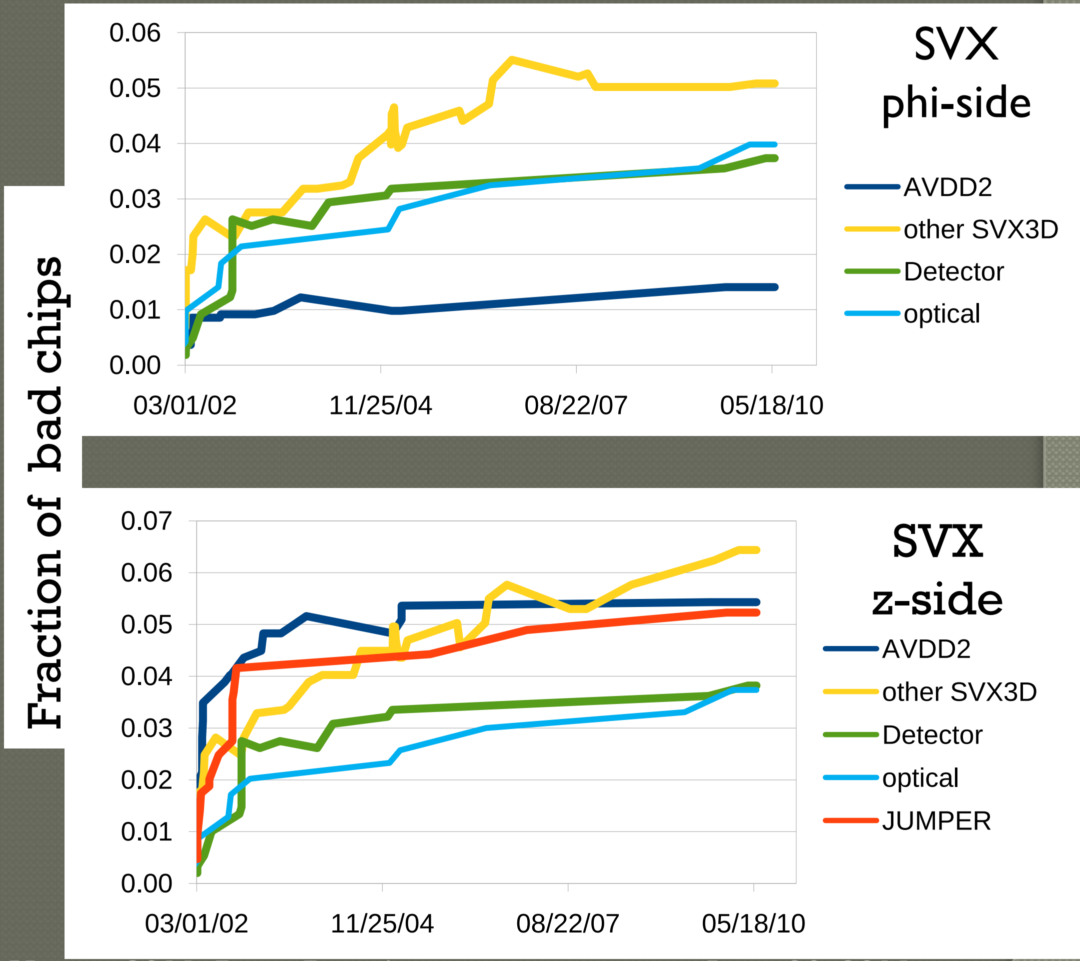
Detector includes port cards, junction cards, cables, power supplies, and the sensors themselves.

Optical is bit errors and failures 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 beam incidents and thermal cycles

Other SVX3D includes all other chip failure modes (internal)



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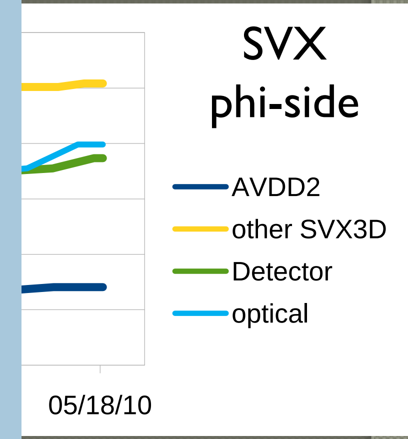
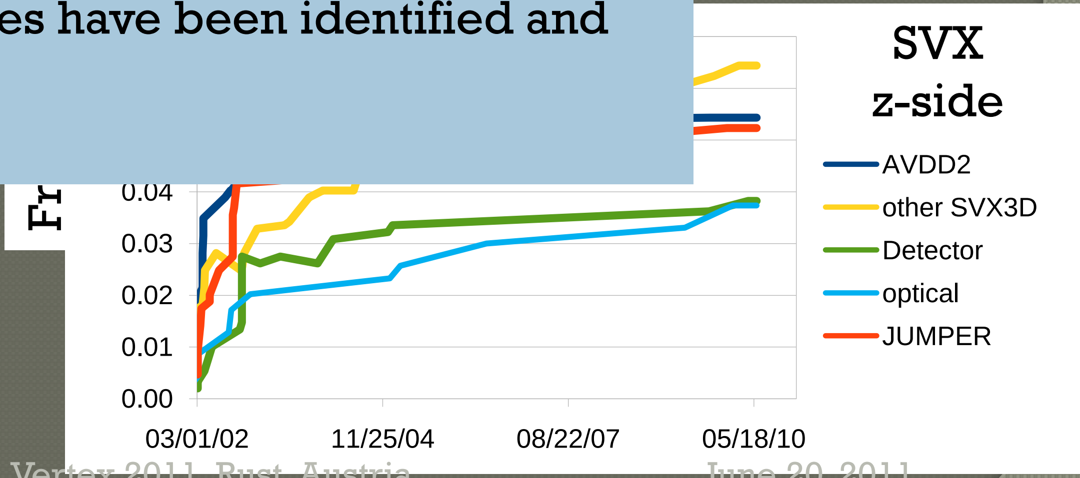
- Optical transmitter (DOIM) failure rate is very very small
- Rate of "Internal chip failures" is stable
  - Radiation damage or time?
  - Mitigated by sparsing out chip (readout threshold=max counts)
  - Symptoms: Stuck or random buffer ID, general garbage data, bit errors local to chip
- Other causes have been identified and addressed





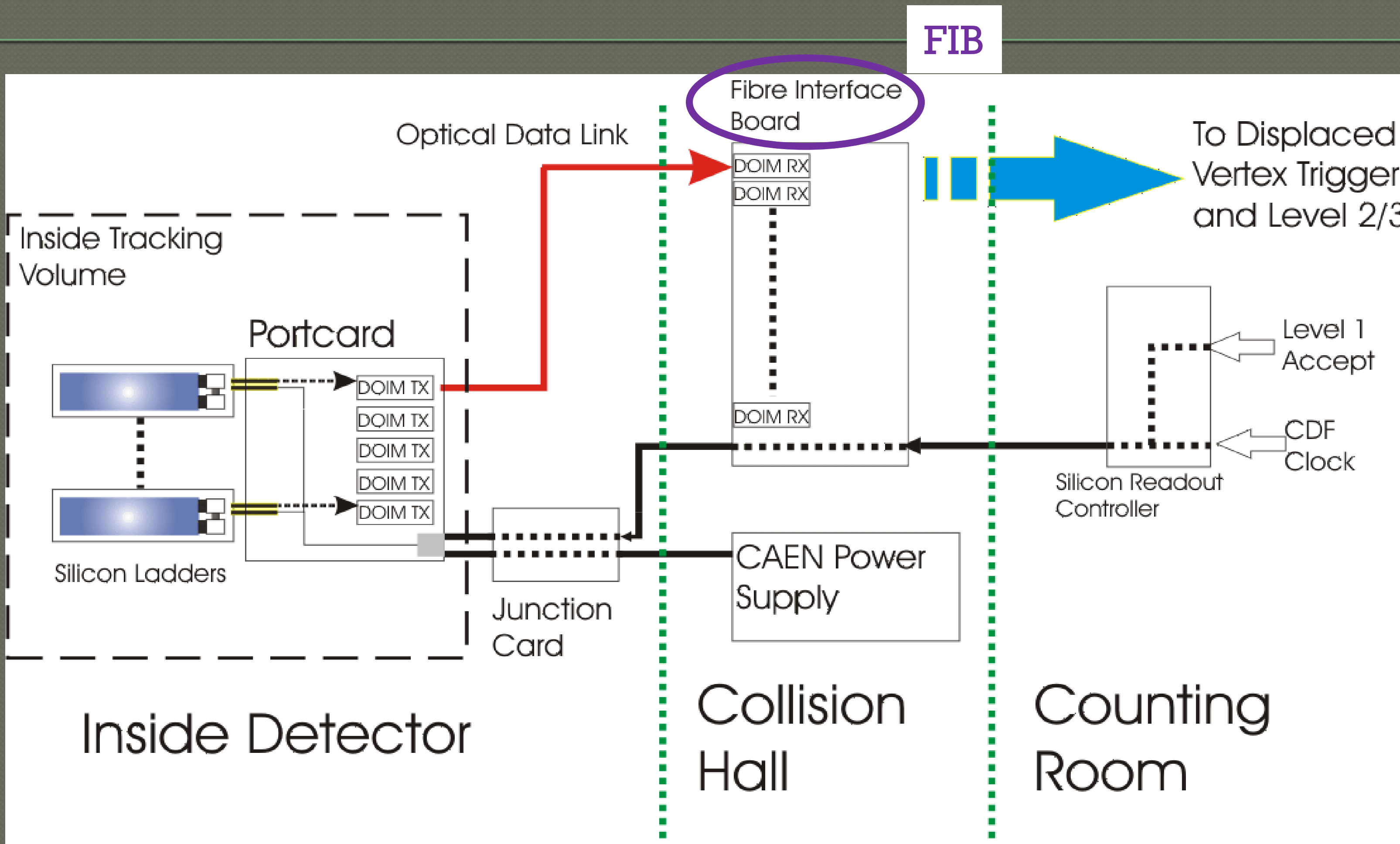
Operational Challenges Past and Present

Operational Challenges

- Chip/hybrid damage caused by
  - Wire bond resonances (SVX only)
  - Thermal cycles
  - Beam incidents
- L00 noise pickup in cables
- Loose cable connections inside the bore
- Corrosion in ISL cooling lines

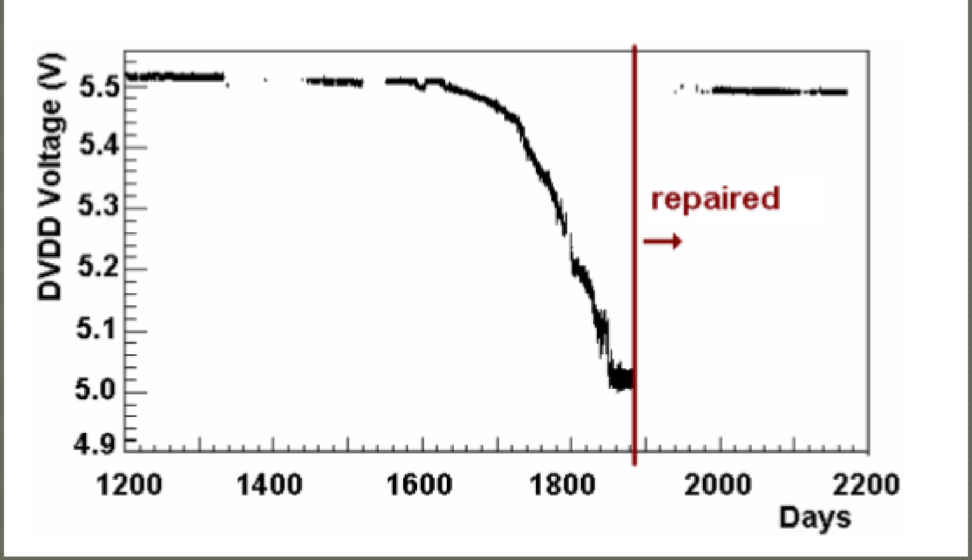
- Radiation damage to electronics
- Staying depleted
- Dwindling manpower resources with high turnover rate

Electronics



Radiation Damage to Electronics

- Power supplies – radiation soft components
  - Soft transistor required overvoltage protection (crowbars) for L00
  - Capacitors loose their "C" after 3-5 fb^{-1} and need to be replaced.



- Takes 4 hours to replace all 36 caps , plus 2 days of testing
- Limited spare pool
- Opening the CDF detector blocks access to supplies

Radiation Damage to Electronics

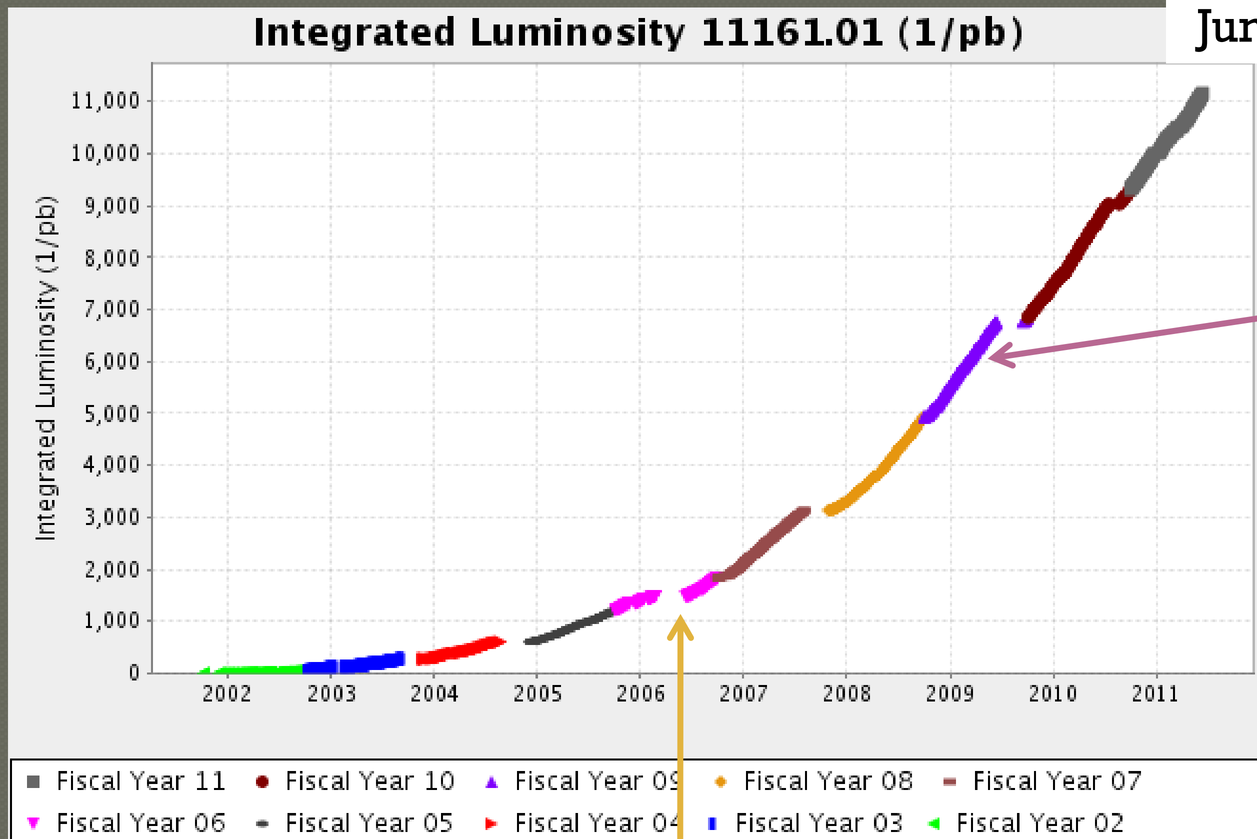
- DOIM-TX light output decreases with dose
  - Only DOIM-TXs originally outside specs are problematic, with one or more low light bits
  - No additional problems expected for Run-II
  - Ultra-sensitive light receivers designed for proposed Run-III just in case
- SEU in FIBs can damage FPGA (~2 per year)
  - high current state blows a fuse, blocks VME bus
  - No data until board is swapped (access)
- CAEN crate RAM destroyed by SEU
  - a few in 10 years, 4 hour access to replace crate

Radiation Damage to Electronics

- FIB crates sprayed, corrupts data stream
  (~1 per month??, ~10 minute recovery)
- Power supply crate needs reset after SEU
  (~1 per 16 hour store, ~2 minute automatic recovery)
- Recover power supply trip
  (~2 per 16 hour store, ~30 second automatic recovery)
- Re-initialize readout chip
  (~2 per 16 hour store, ~10 second automatic recovery)

Automatic recovery systems are essential to minimize down time.

June 14, 2011



Voltage increases every 3-6 months

First voltage increases needed

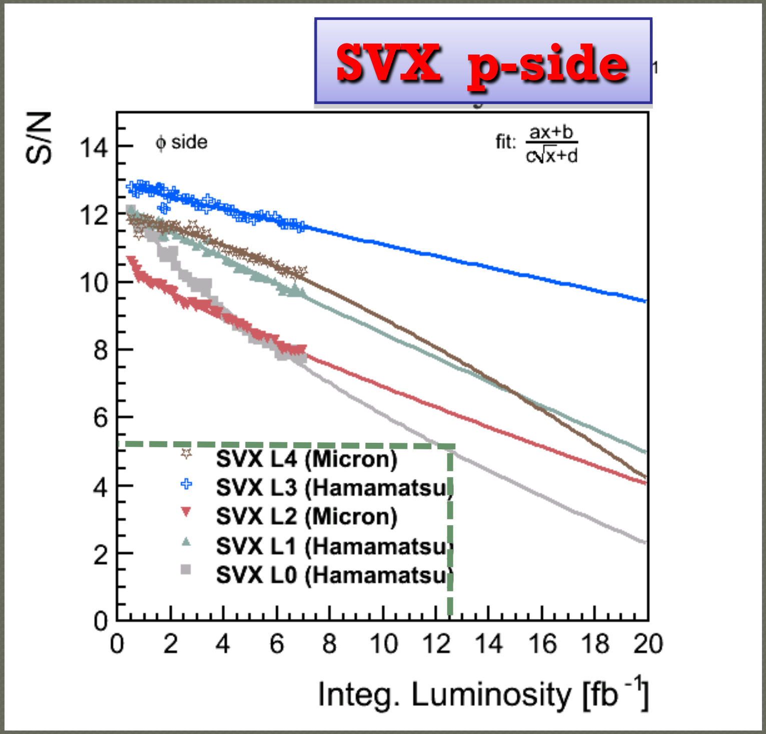
Staying Depleted

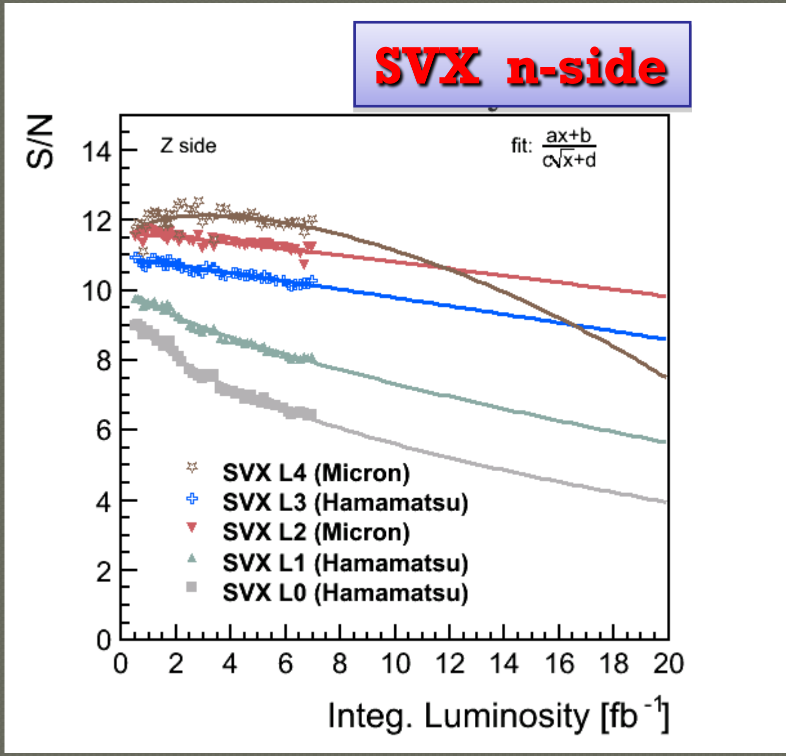
- Measuring the depletion voltages is expensive
  - 2 hours of collisions not used for physics (per layer measured)
  - Black box to analyze data quickly is essential!
- Raising the voltages is time consuming
  - small voltage steps
  - handful of ladders at a time to minimize risk
  - monitor for damage and noise afterward
- Power supplies have internal protection limits for bias voltages, must be removed from CH to change
- In 2010, 3 of 15 L00 power supplies failed when raised from 250V to 350V and needed repairs (originally tested to 500 V).

Aging Studies

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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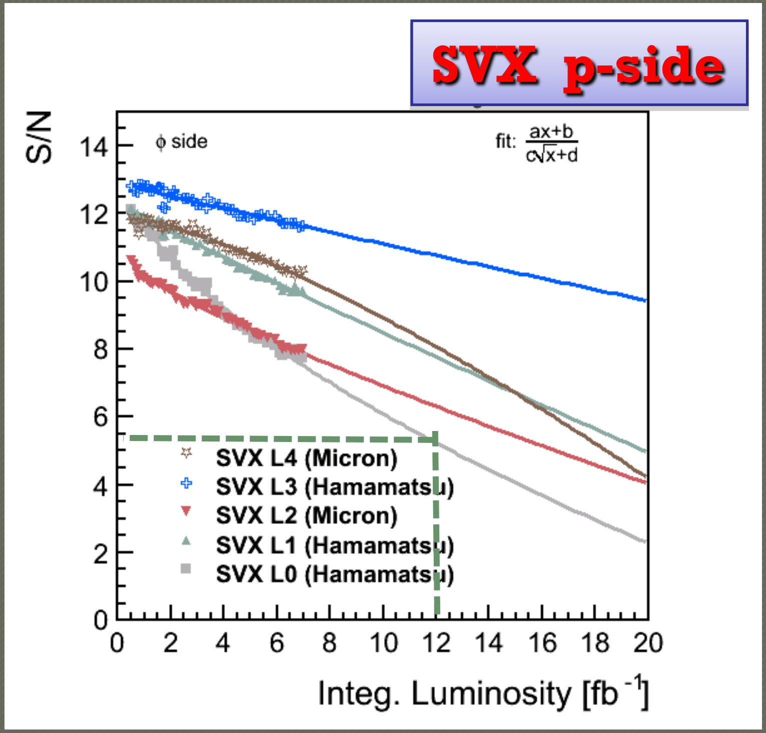
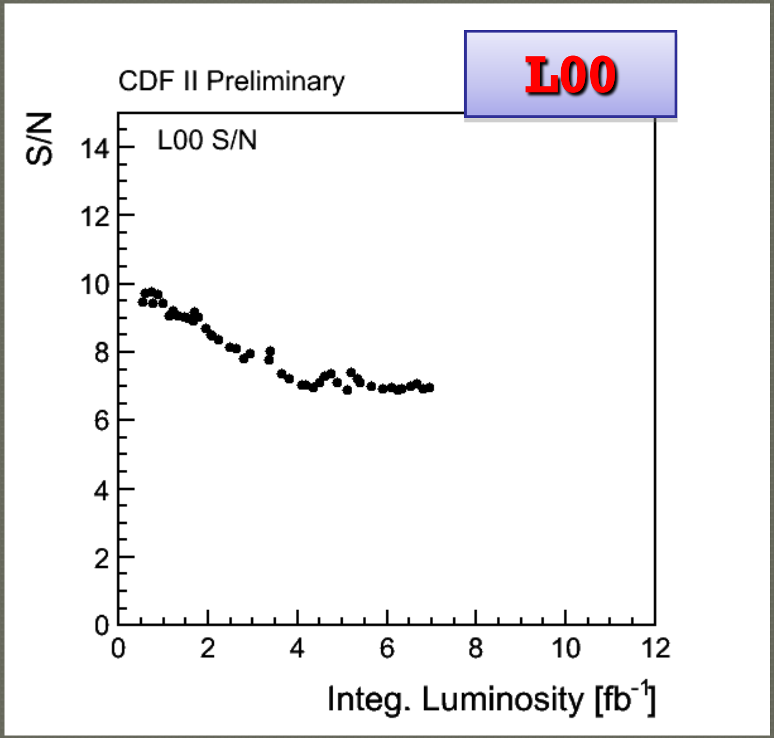
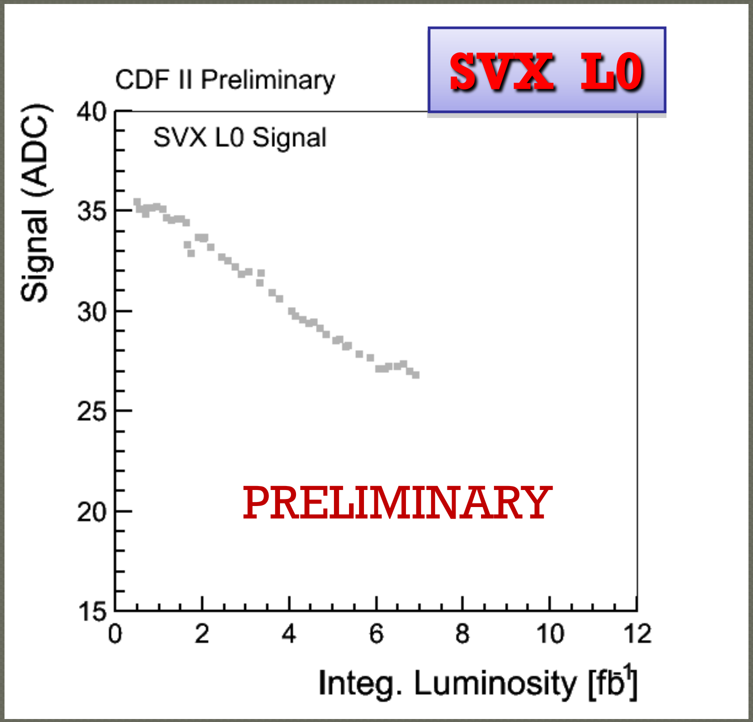
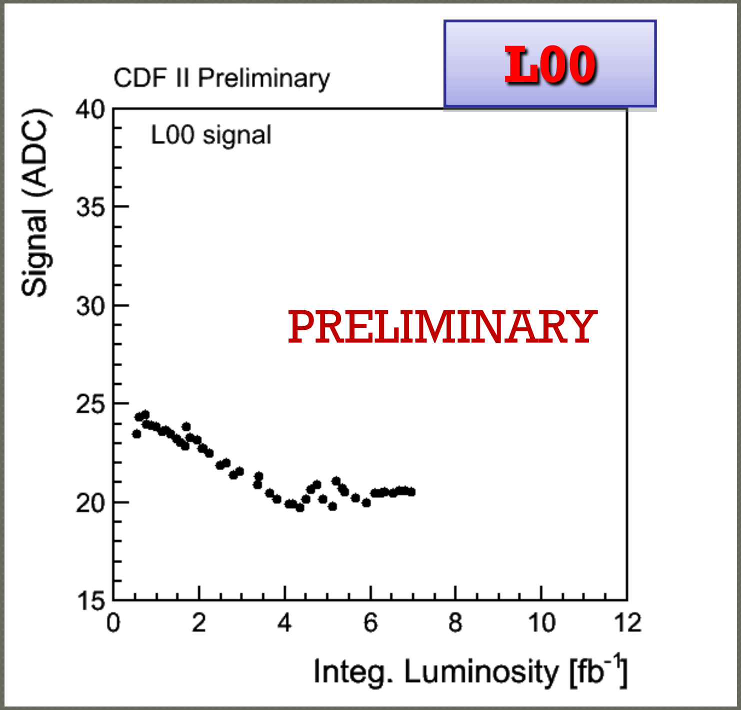




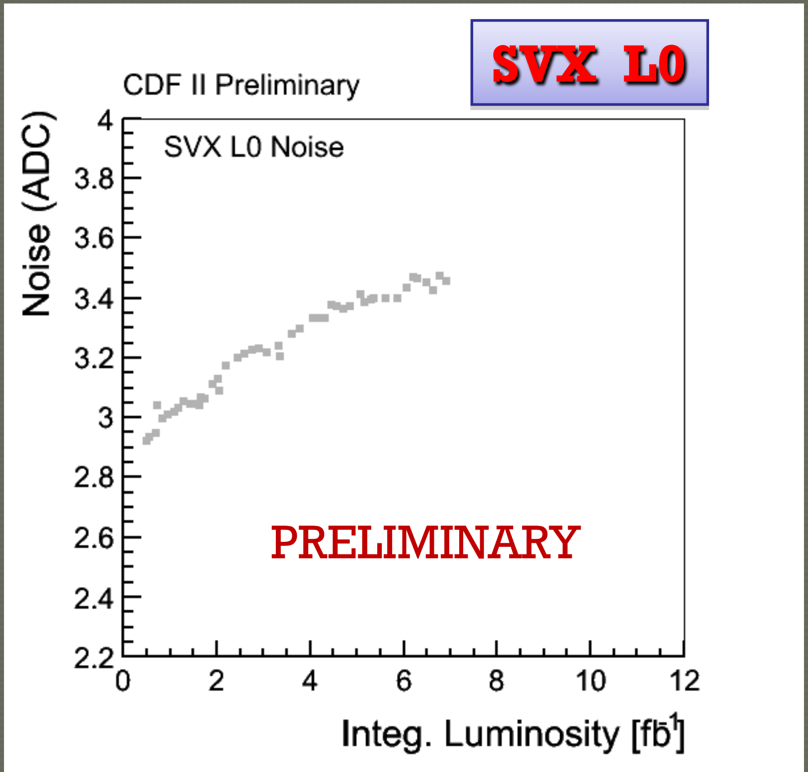
Unexpected signal decrease

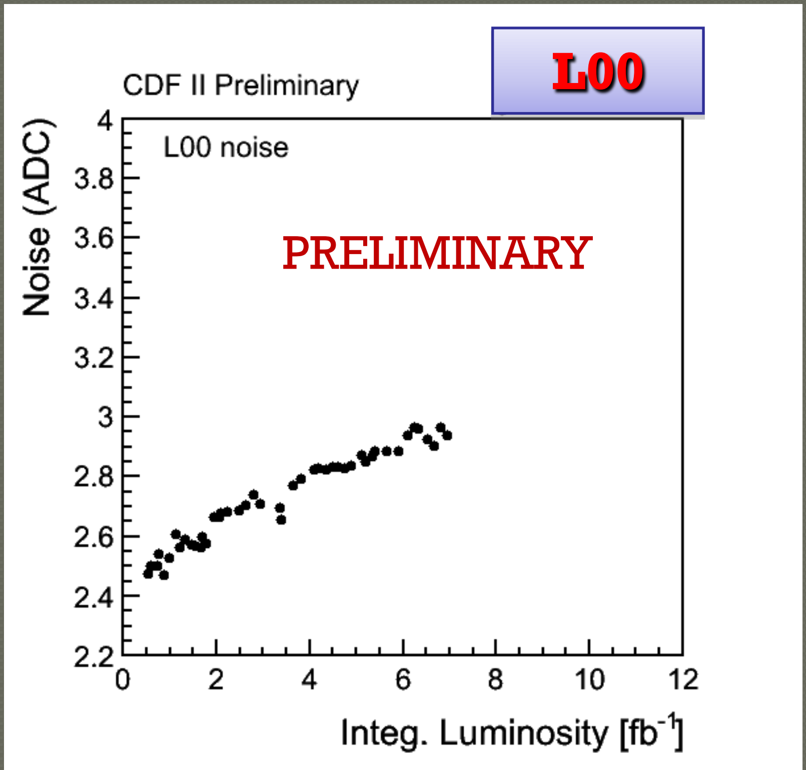




No significant decrease in the signal (total cluster charge) was foreseen.

Measured Noise

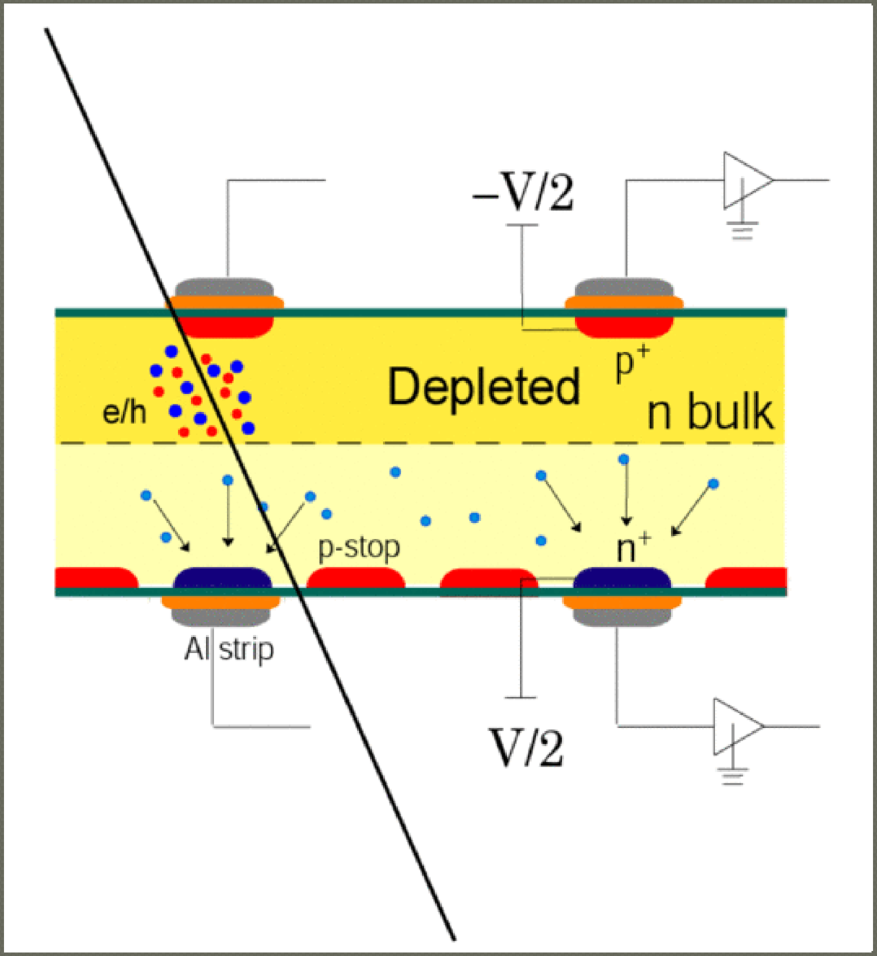




Noise increase less than predicted, but coolant temperature was lowered

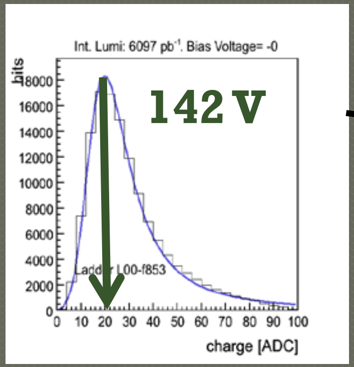
Similar behavior for different radiation dose – colder sensors, shielded hybrids, or both?

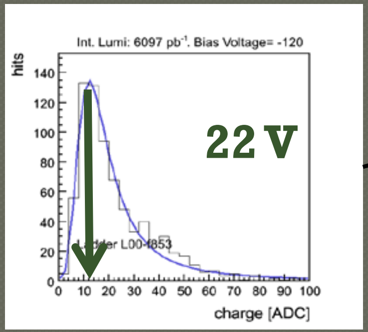
Depletion Voltage

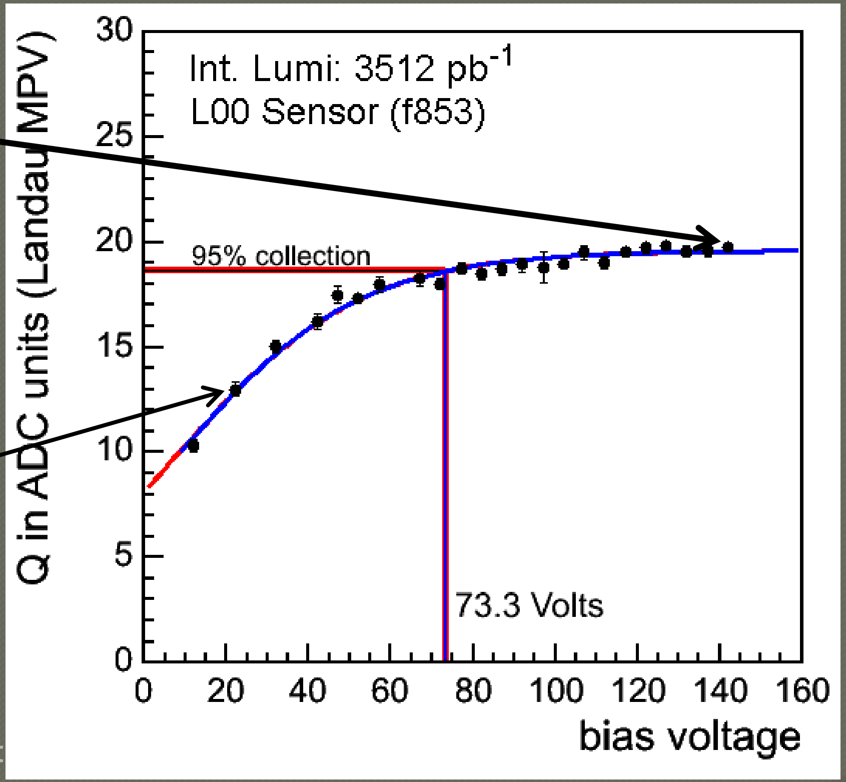


Depletion Voltage Measurement

- 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

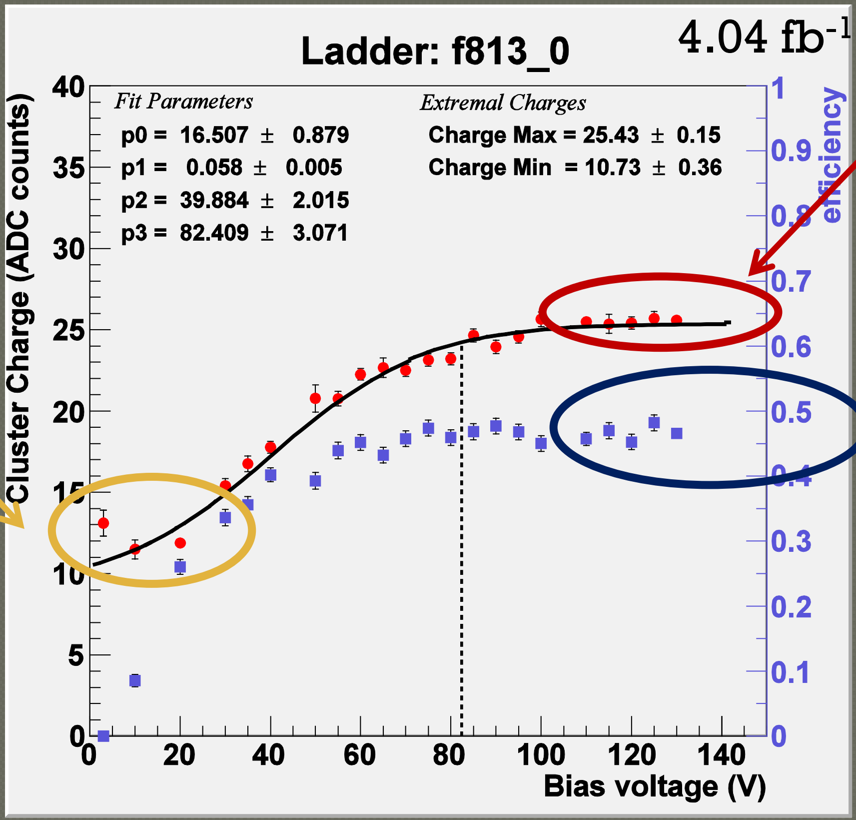






Operational Perspective

Standard offline clustering threshold (depends on measured noise of individual strips)

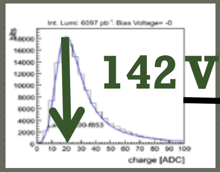


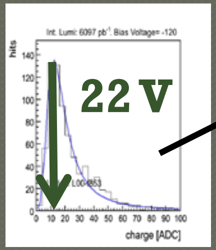
"S" portion of S/N

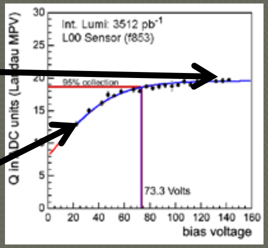
Probability to find a cluster for a given track

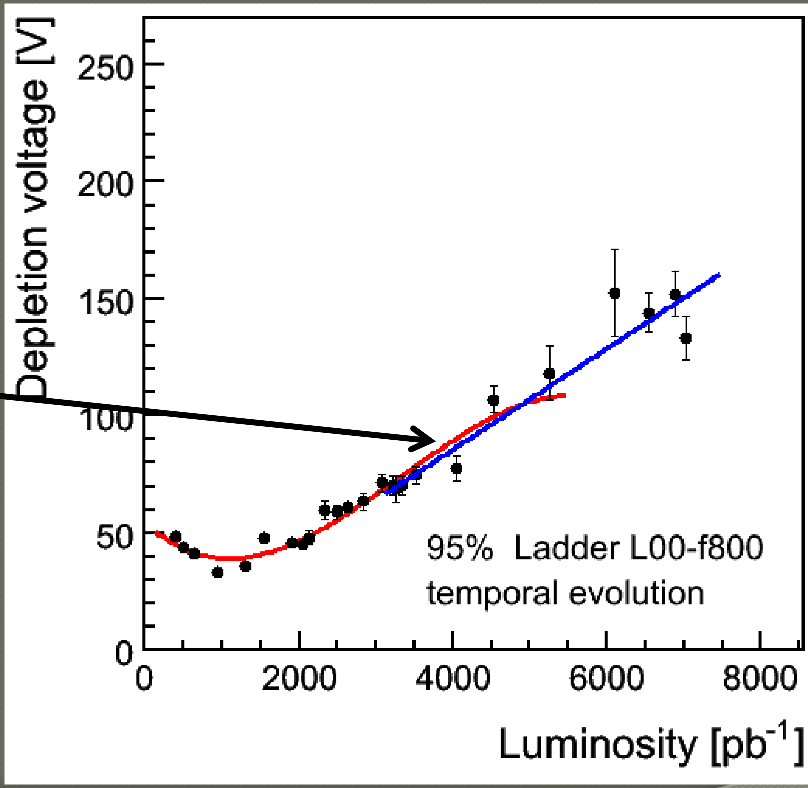
Depletion Voltage Measurement

- 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

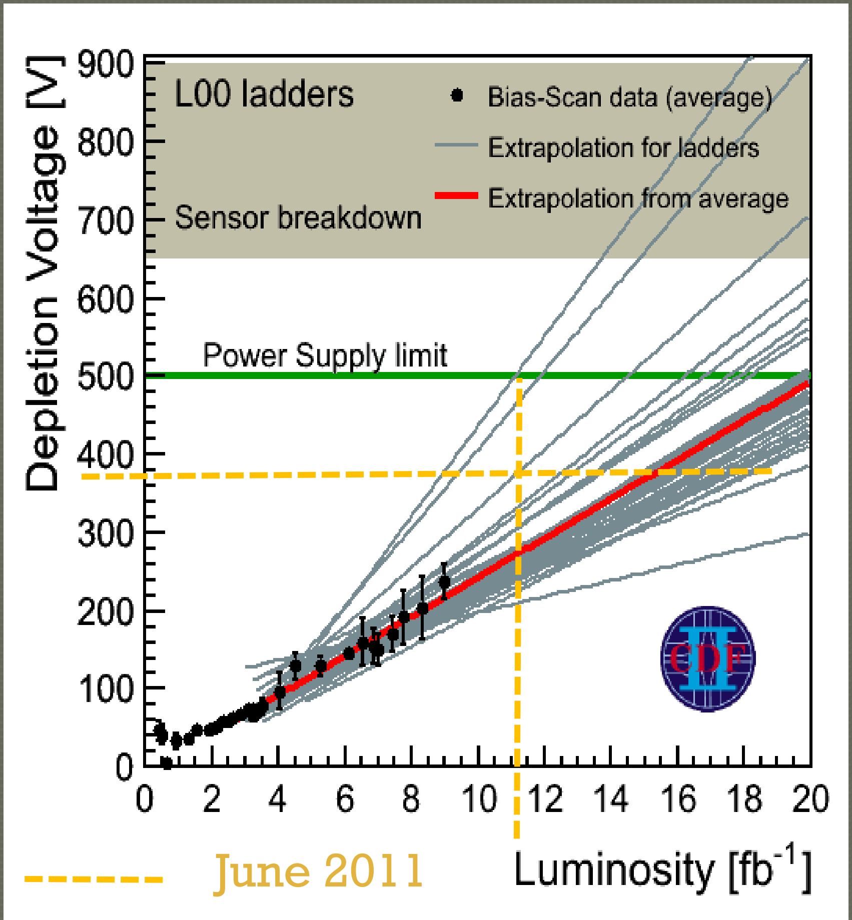


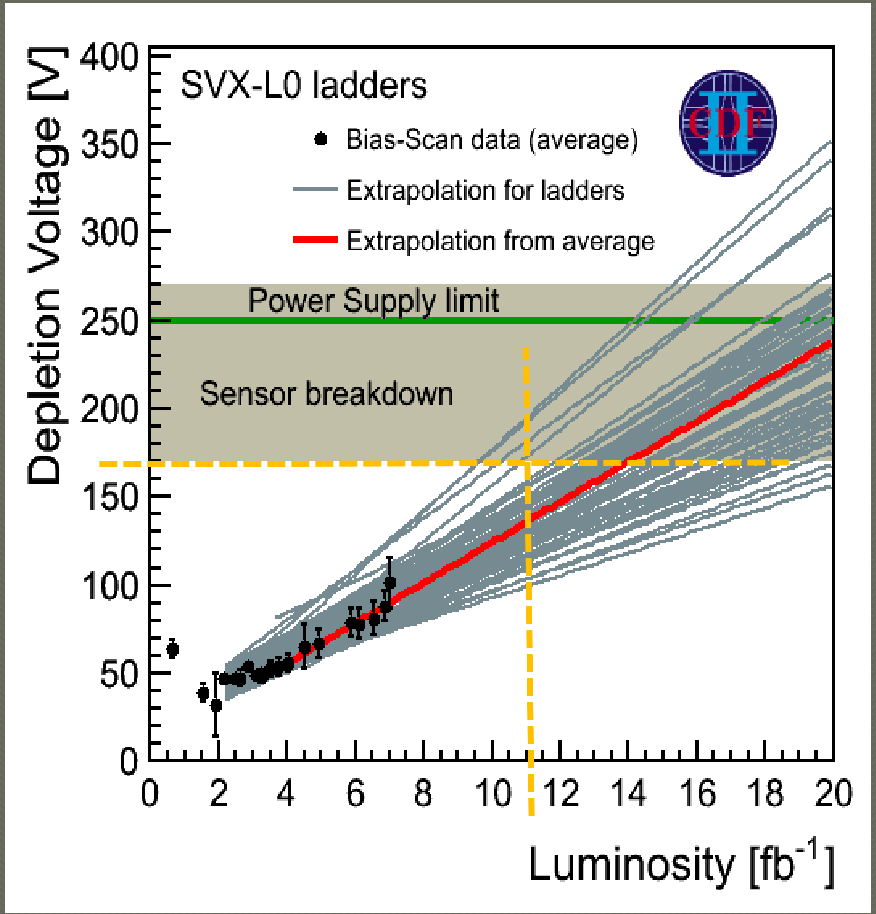






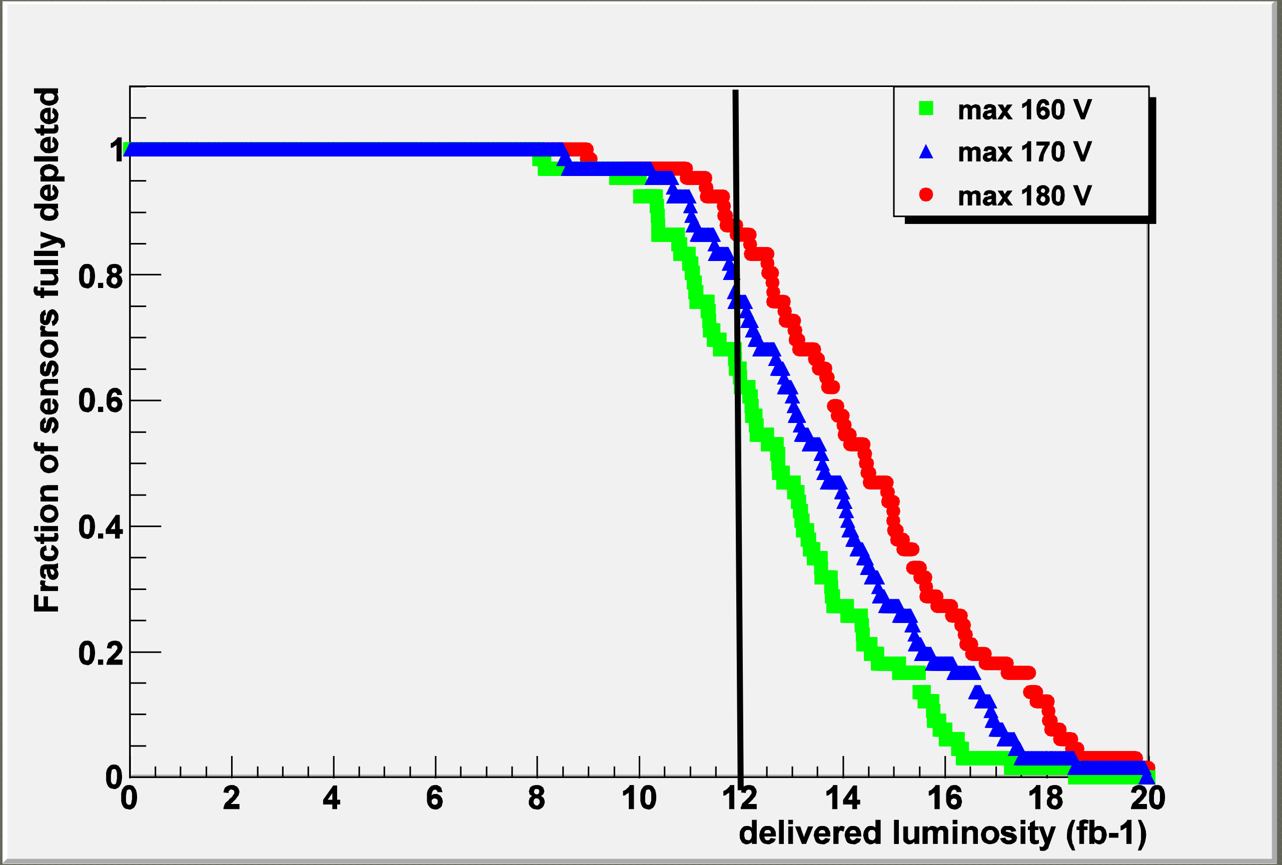
Depletion Voltage Projections





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

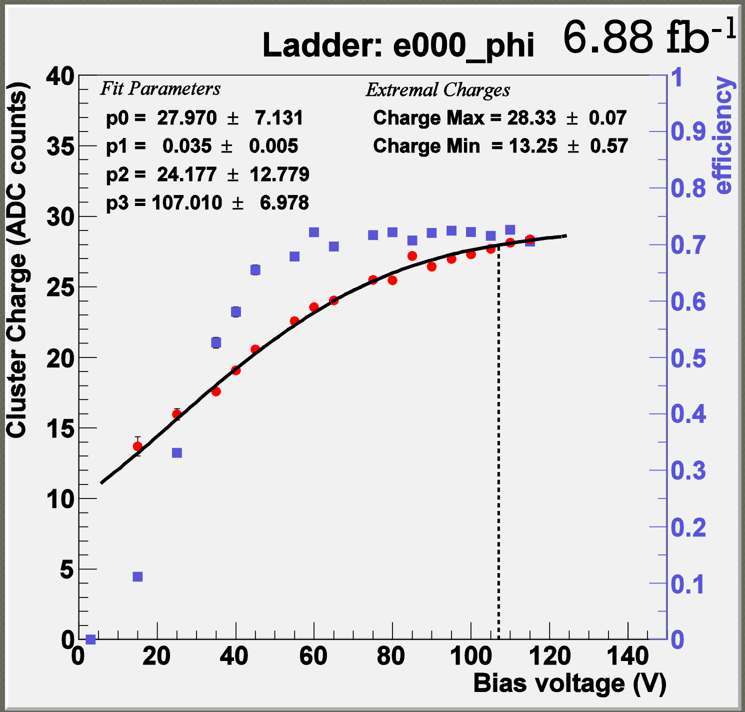
- All ladders at 165 V currently
- Breakdown voltage is uncertain
  170-200V
- At 160V, loss of efficiency expected for only 3 of 72 ladders

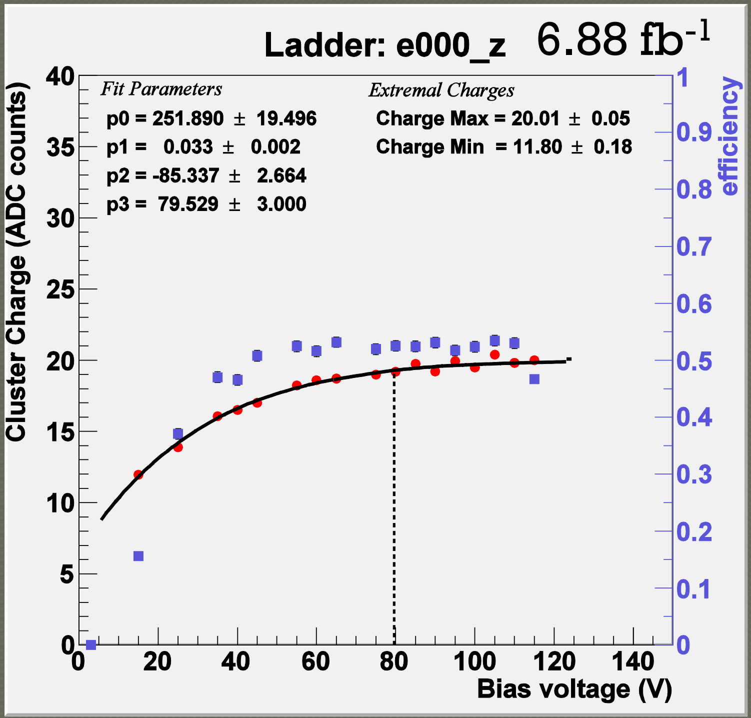


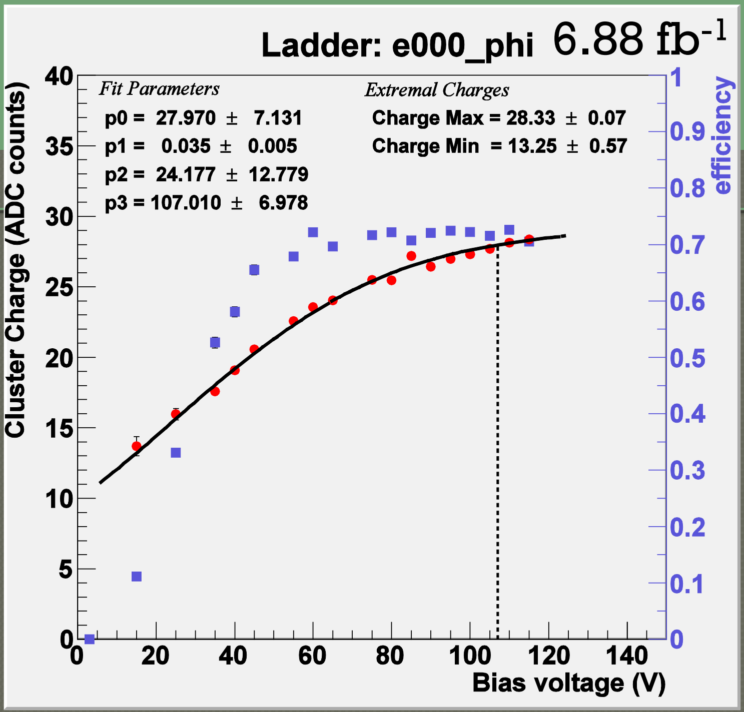
*updated data analysis , may not match previous slides exactly

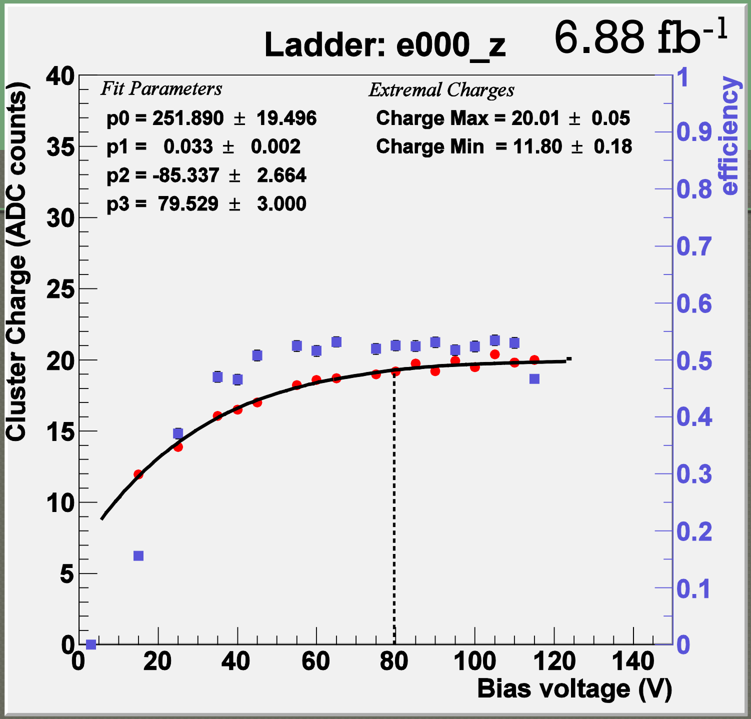
Underdepleted ladders

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







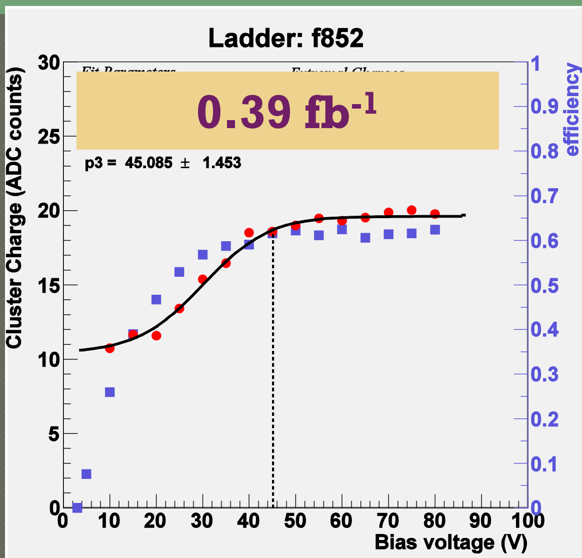


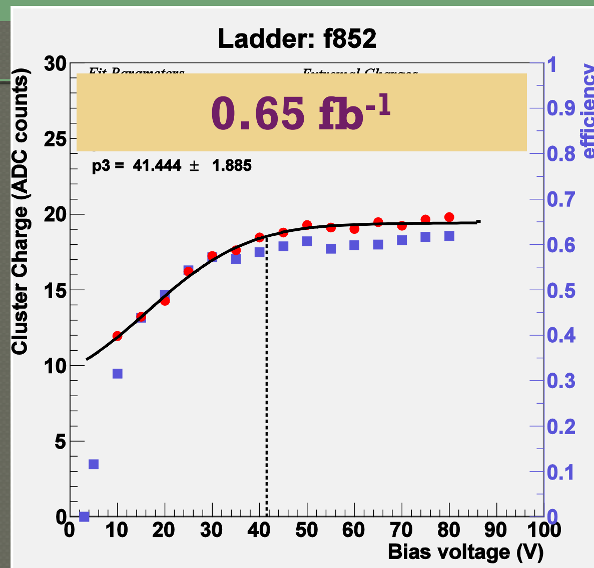
Qualitative observation

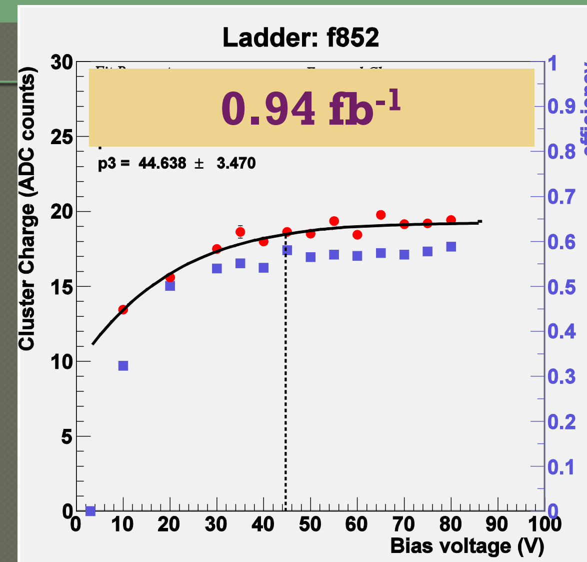
- The (heavily irradiated) sensors are depleting from the two sides toward the center
- Consistent with a doubly-peaked electric field

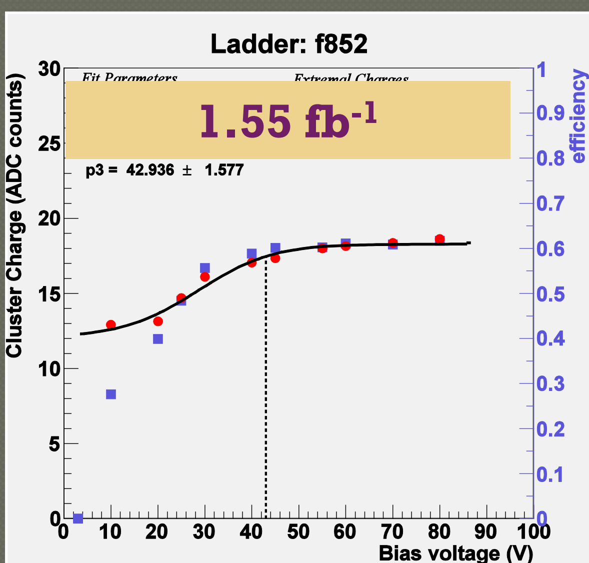
NIMA 565 p 212 (2006)

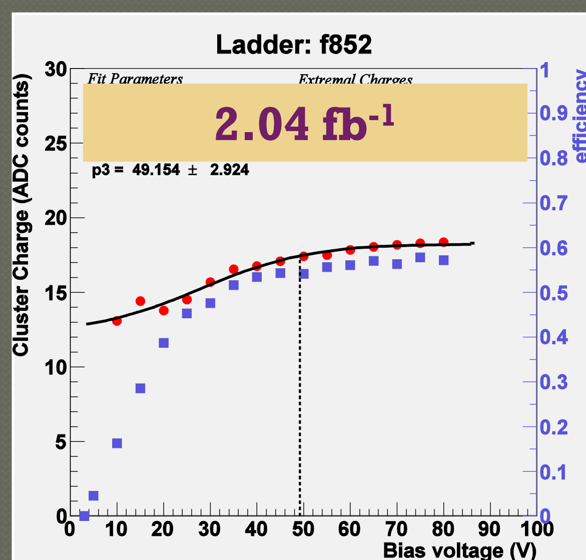
L00 evolution





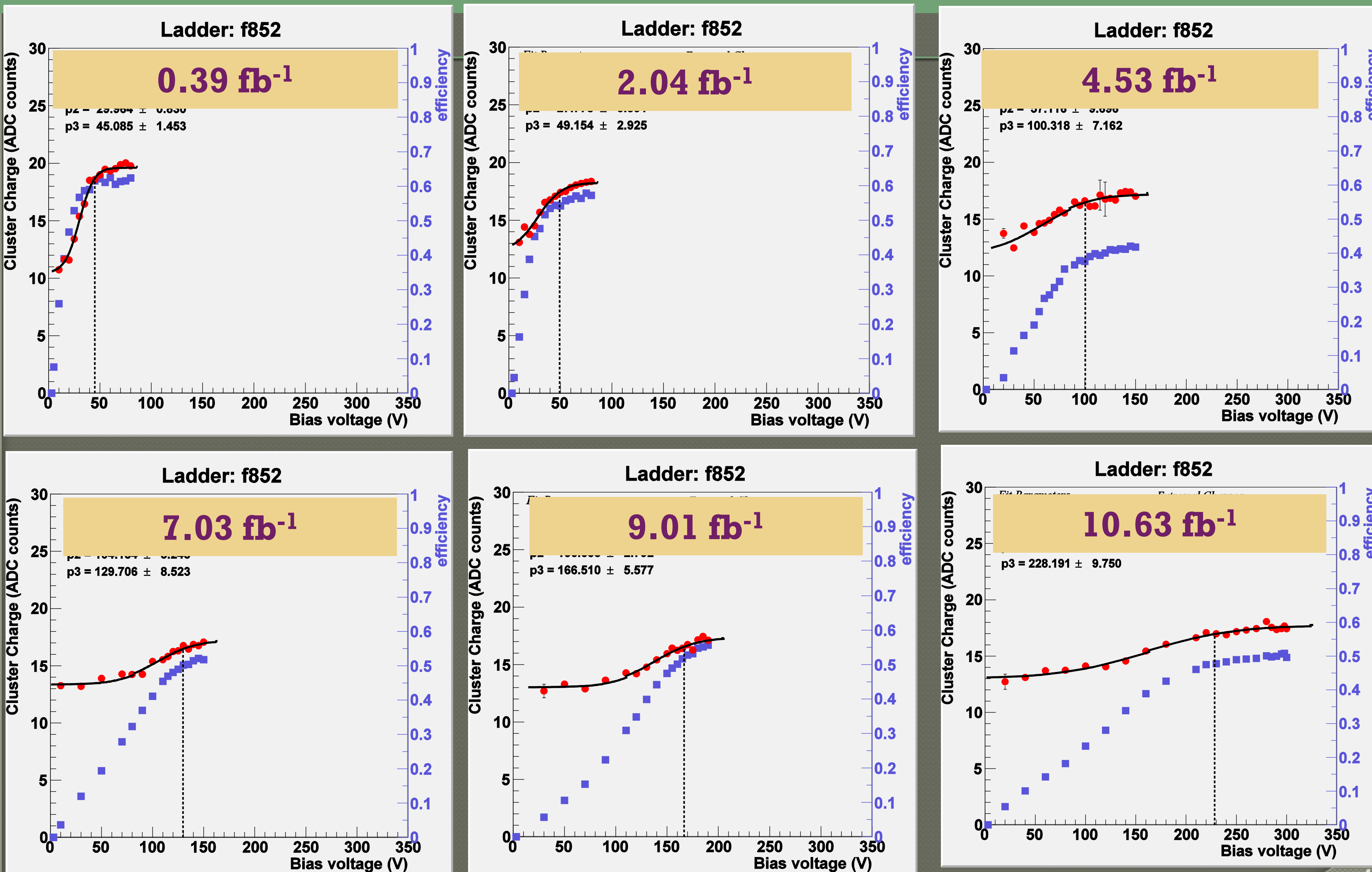




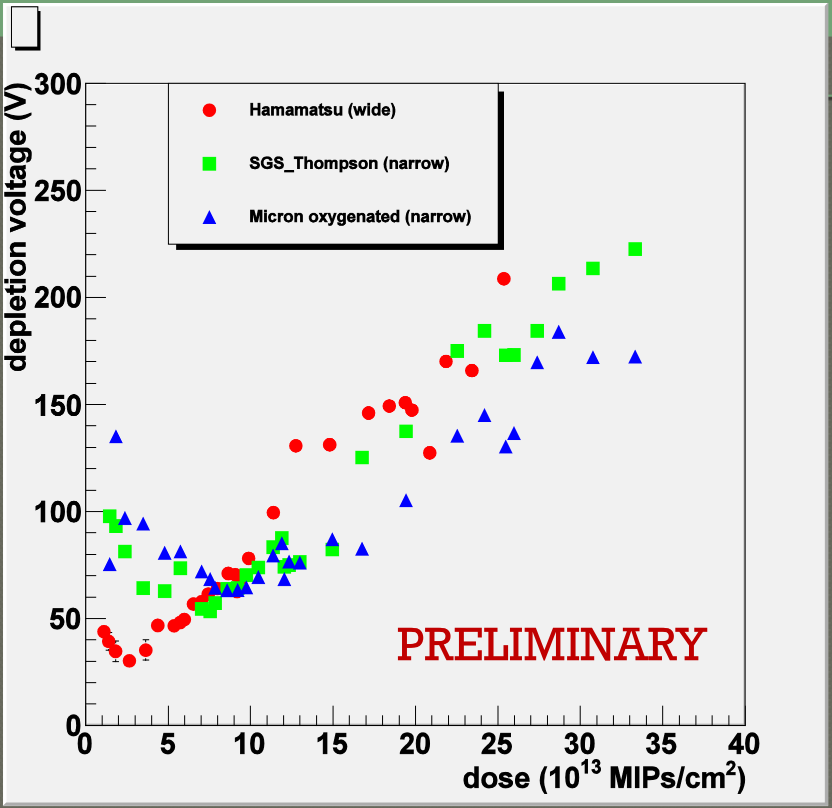


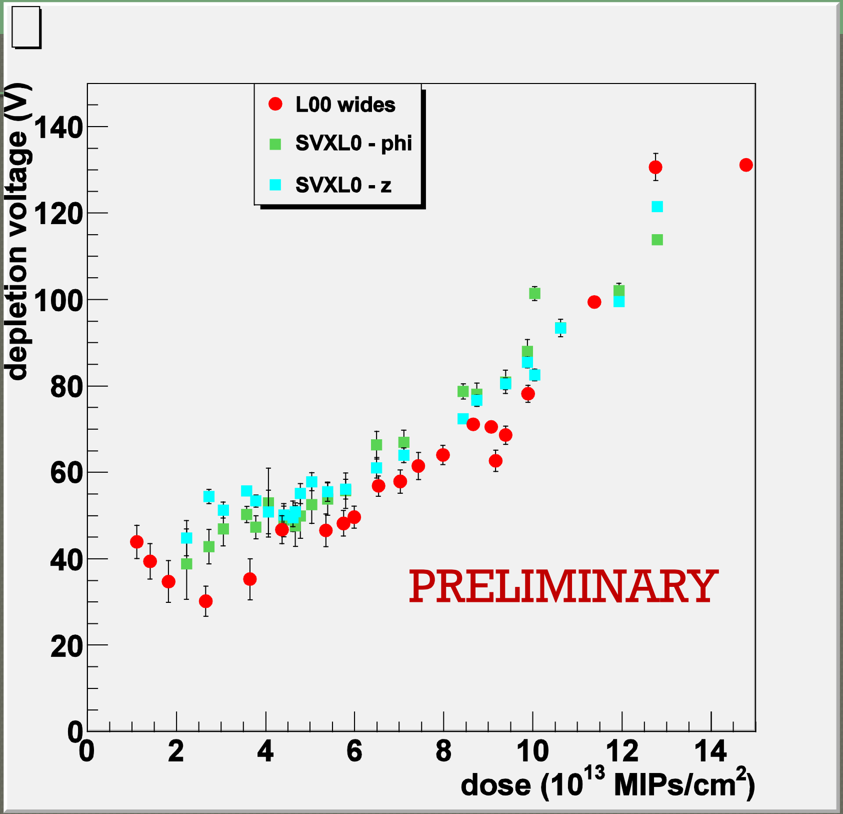
After inversion, sensors still “work” when under-depleted!

L00 evolution



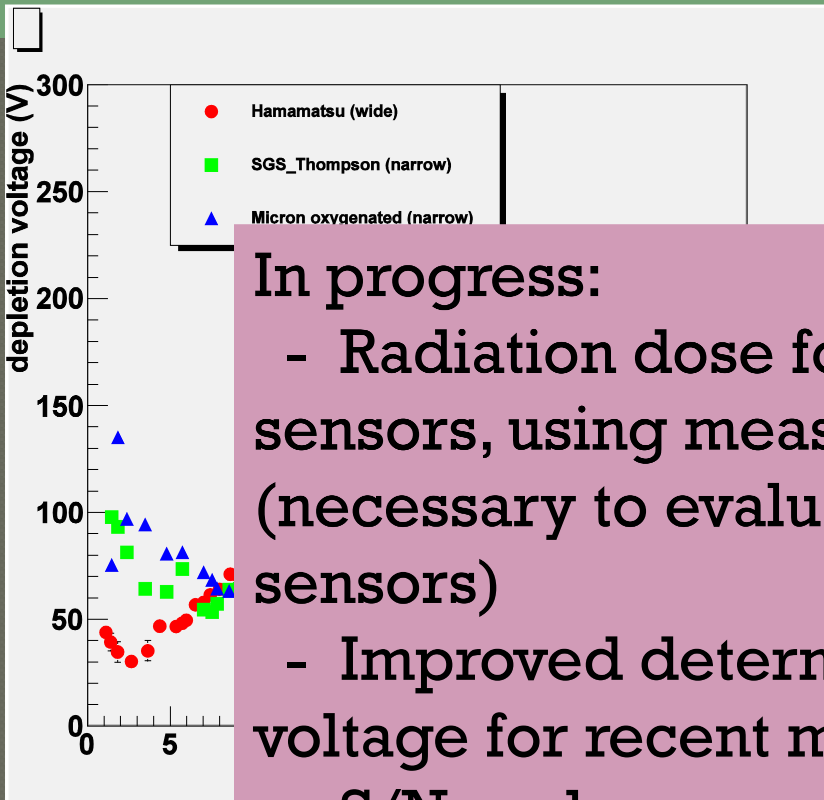
Future Plans

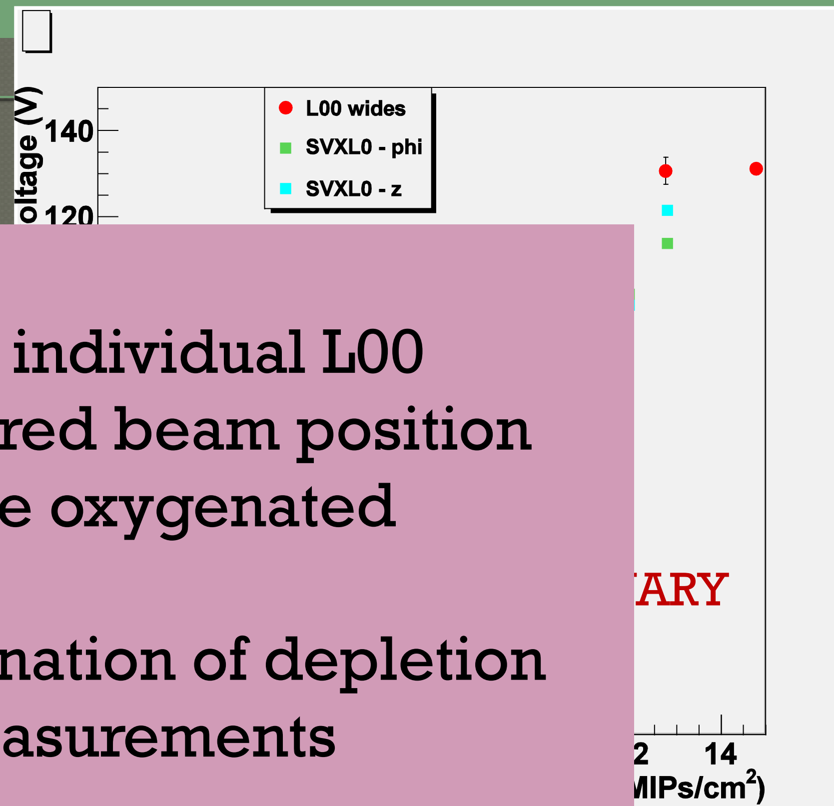




- Depletion voltage is averaged over all sensors in a layer
- Assume interaction region is at the center of the detector
- Conversion from luminosity to MIPs/cm^2 comes from the TLD measurement of CDF radiation field (NIM **A514** (2003) 188), assuming the contribution of photons and low energy neutrons to the TLD measured values is negligible.

Future Plans





In progress:

- Radiation dose for individual L00 sensors, using measured beam position (necessary to evaluate oxygenated sensors)
- Improved determination of depletion voltage for recent measurements
- S/N vs dose

• Depl

• Assu

• Conversion from luminosity to MIPs/cm^2 comes from the TLD measurement of CDF radiation field (NIM **A514** (2003) 188), assuming the contribution of photons and low energy neutrons to the TLD measured values is negligible.

Summary and Conclusions

Tevatron data offer unique measurements of radiation damage in silicon detectors

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

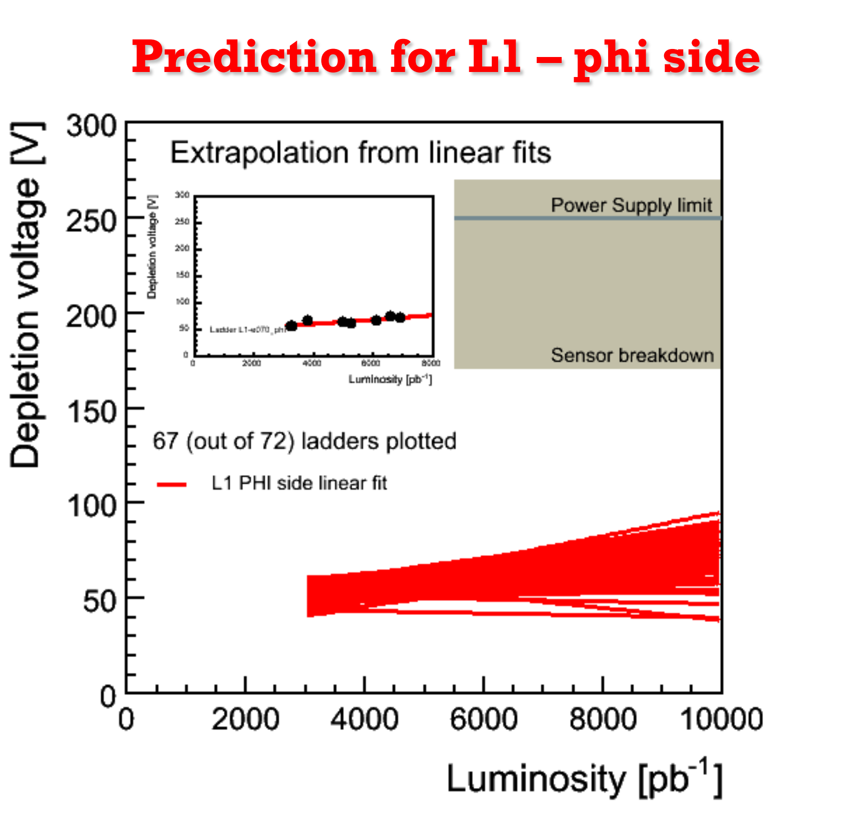
Our heavily irradiated sensors are behaving differently than expected:

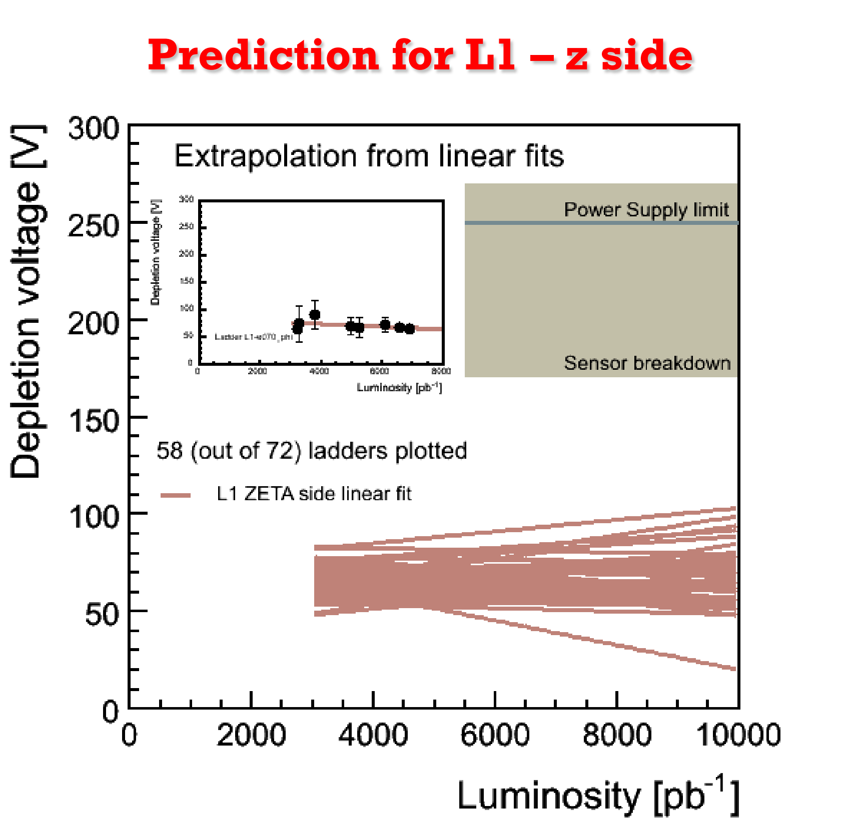
- The S/N predictions differ from the measured data (20% signal loss for innermost sensors)
- Slightly underdepleted sensors still give good data on both sides of the sensor.

Qualitative confirmation of double-peaked electric field inside heavily irradiated sensors

Backup Slides

Depletion Voltage Projections





Michelle Stancari
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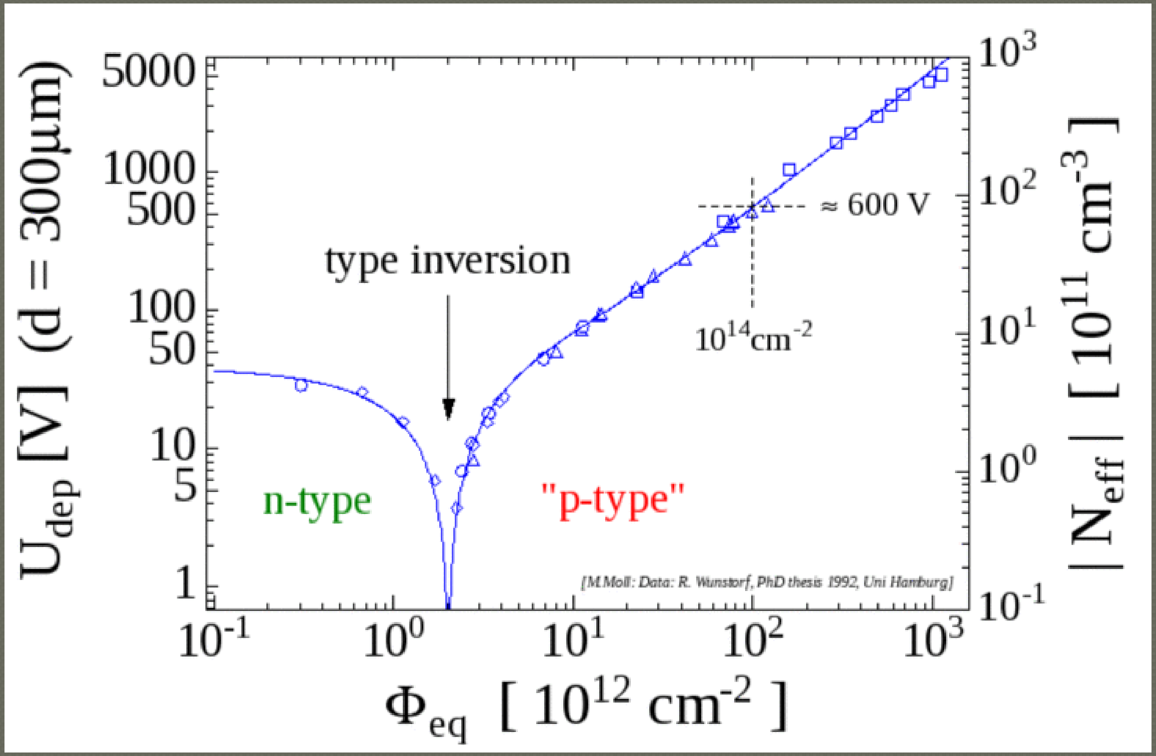
Depletion Voltage

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

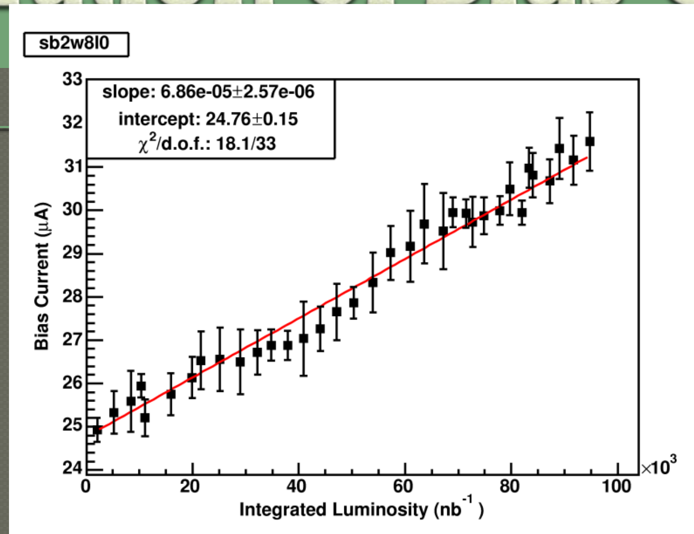


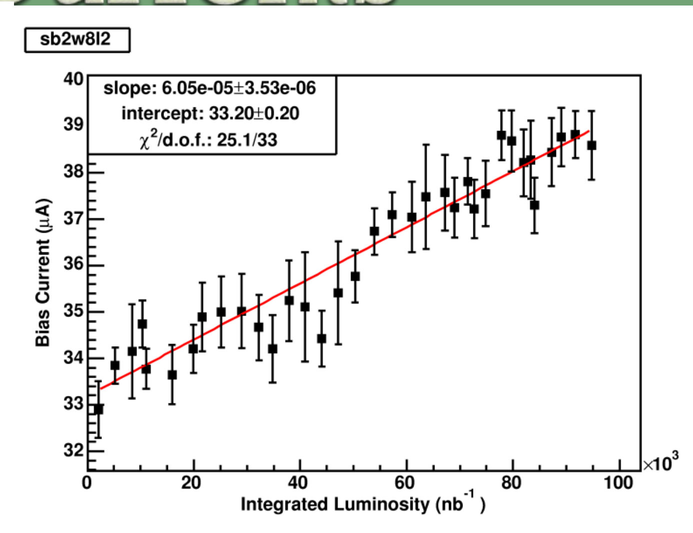
$$U_{dep} = \frac{qND^2}{2\varepsilon}$$

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

Evolution of Bias Currents

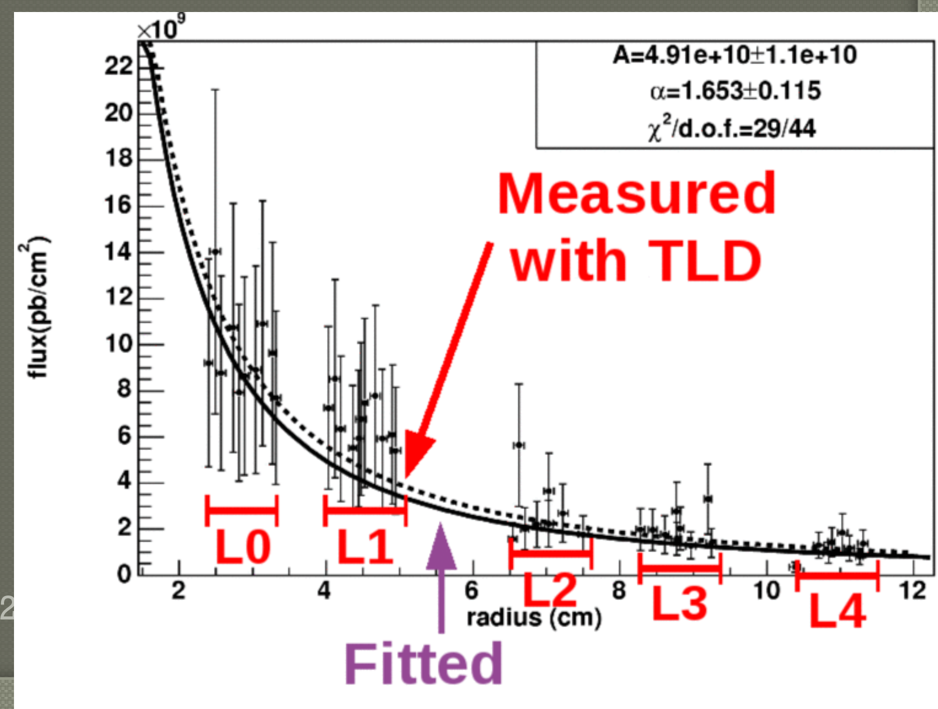




- α_{dam} is constant for several orders of fluence
- The **fluence – integrated luminosity relationship** depends on distance of the sensor to the beam

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

- 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).



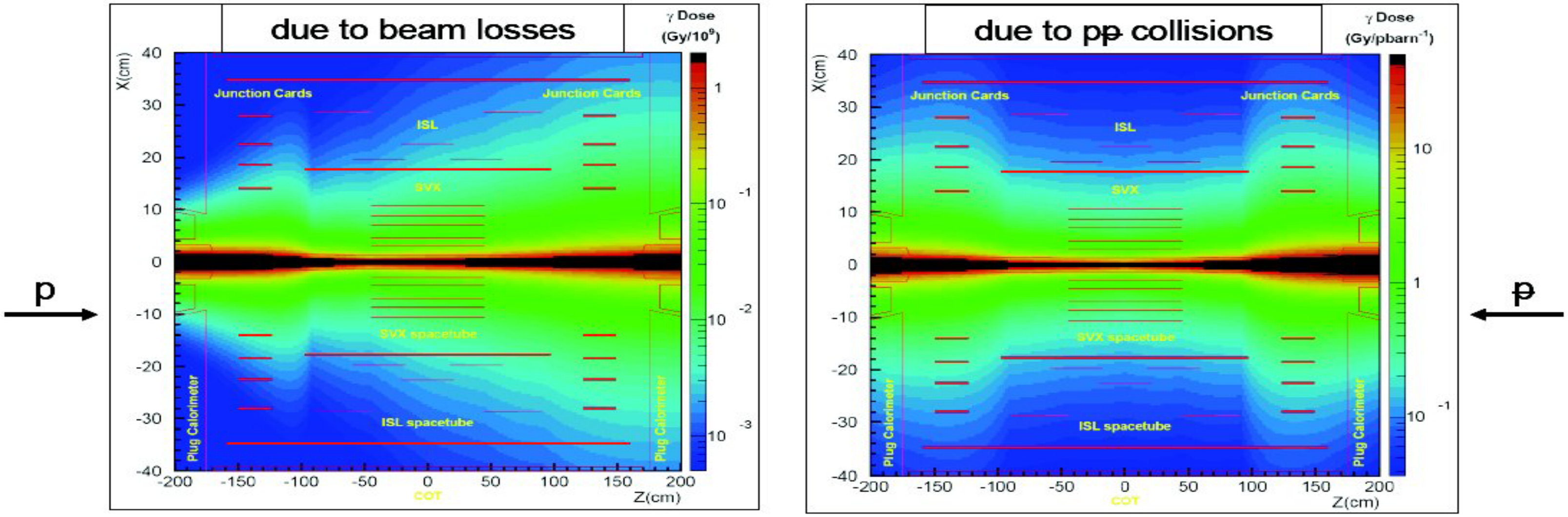
SVX details

Property	Layer 0	Layer 1	Layer 2	Layer 3	Layer 4
number of ϕ strips	256	384	640	768	896
number of Z strips	256	576	640	512	896
number of ϕ chips	2	3	5	6	7
number of Z chips	2	3	5	4	7
stereo angle	90^o	90^o	$+1.2^o$	90^o	-1.2^o
ϕ strip pitch (μm)	60	62	60	60	65
Z strip pitch (μm)	141	125.5	60	141	65
total width (mm)	17.140	25.594	40.300	47.860	60.170
total length (mm)	74.3	74.3	74.3	74.3	74.3
active width (mm)	15.300	23.746	38.340	46.020	58.175
active length (mm)	72.43	72.43	72.38	72.43	72.38
number of detectors	144	144	144	144	144

Table 5.3: Silicon detector mechanical dimensions

CDF Radiation Field

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



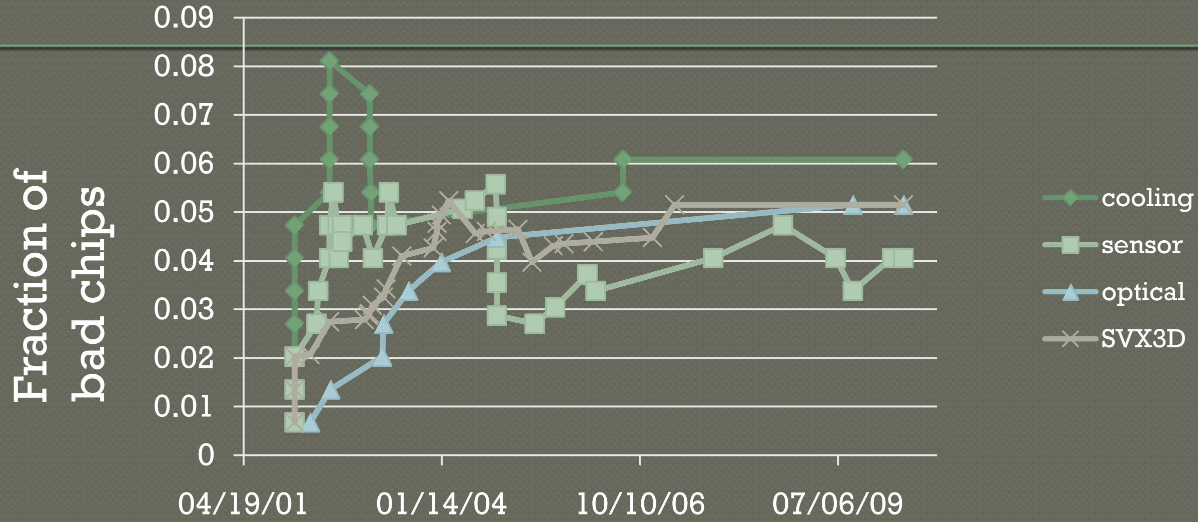
(See R. J. Tesarek *et al.*, IEEE NSS 2003)

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

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

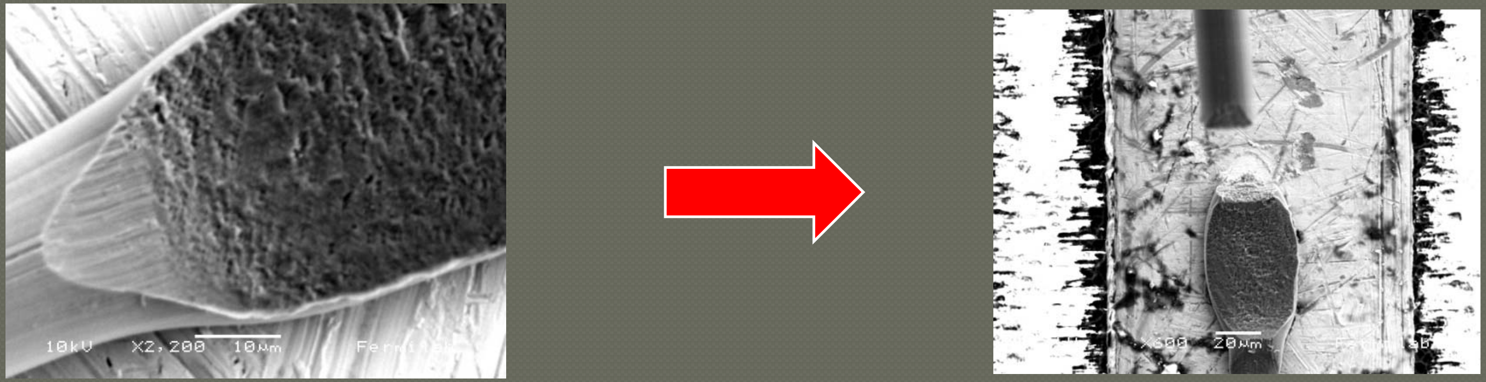
- Ionizing radiation dose at r = 3 cm, |z| < 45 cm: 300 ± 60 kRad / fb^{-1}
- Use fluence conversion, 1 rad = 3.87×10^{7} MIPs/cm^2, to predict integrated dose

Chip accounting - ISL



- No jumper failures for ISL because readout happens only after L2 accept
- No AVDD2 failures because of warmer temperature than SVX
- Sensor recovery after JC pushes (disconnected cables)
- Long history of cooling problems
  - 2003 – unblocked cooling lines
  - 2007 – major leak repaired

Wire Bond Resonances



$$\vec{F} = i\vec{L} \times \vec{B}$$

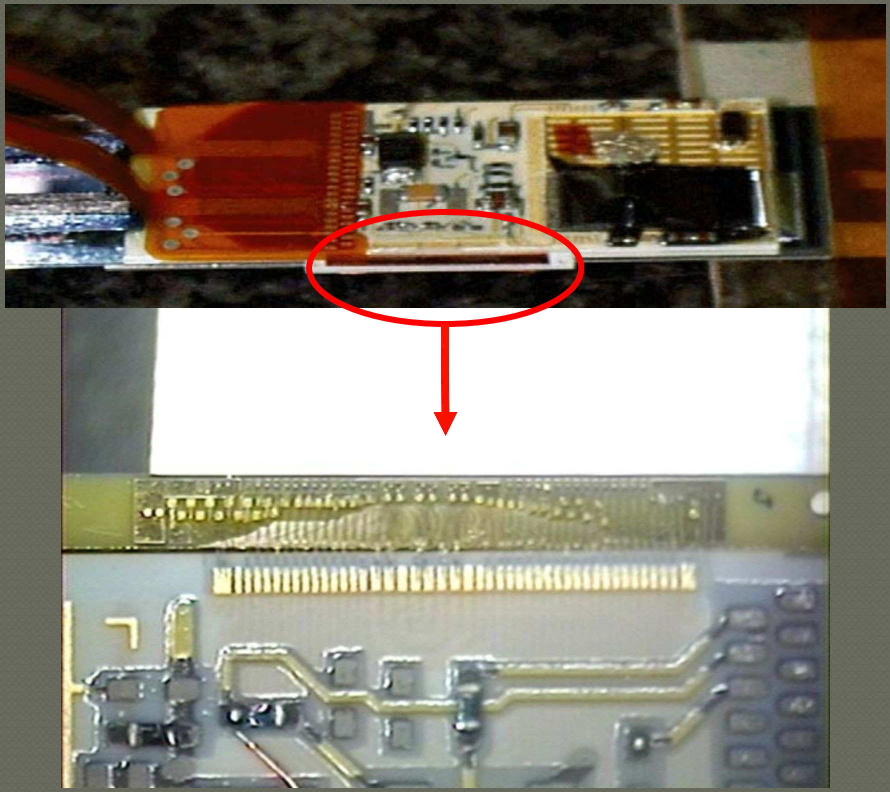
- Lorentz Force
- Wire bonds with current in the 100 mA range can on oscillate if pulsed at the right frequency
- Fatigue induces cracks on the heel
- Amplitude of oscillations is consistent with a few wire diameters
- Test show that oscillating bonds break in minutes
- Certain trigger conditions cause the wires to resonate

Wire Bond Resonances

Manifestation
- Jumper wires are the path for control, power and data to pass from one face of the hybrid to the other
- When this breaks, the chips for the z-side of the sensor have no power

Survival Tactic
- Limit the L1A rate to 35 kHz (hard) and 30 kHz (soft)
- "Ghostbuster" monitors for resonance conditions and halts the DAQ.

Solution (too late for CDF)
- Encapsulant (silicone elastomer) placed by hand over the foot of the bond (Bolla, VERTEX2003)



Preventing Chip Damage

THERMAL CYCLES

- Flow cold, dry N2 gas in closed volume around detector
- Keep coolant cold

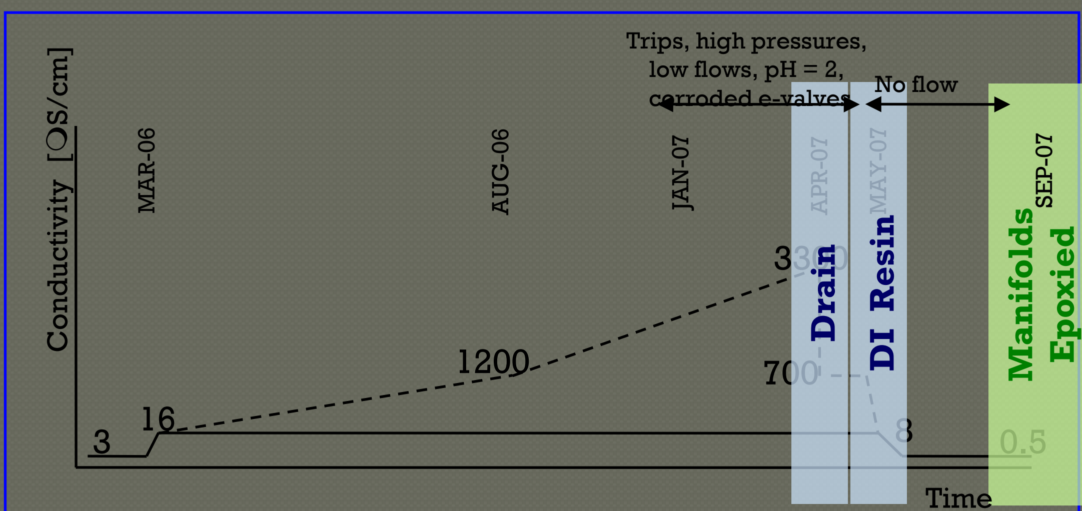
BEAM INCIDENTS

- New collimator!
- Diamond beam abort

ISL Cooling System: The Saga of 2007

The Problem

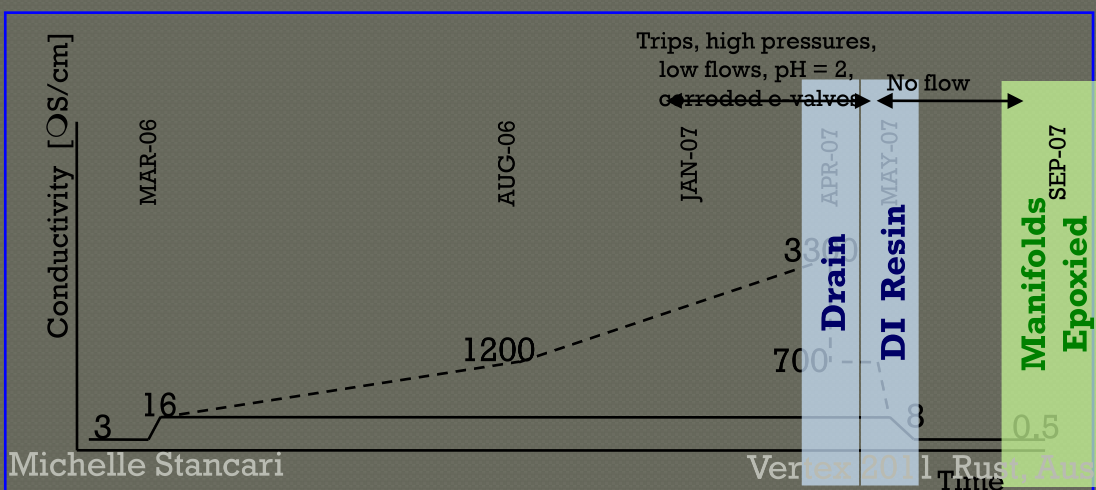
- In 2007, bad vacuum in ISL indicates presence of leaks. Eventually, east side bad enough to interfere with detector operations.
- Found high acidity in coolant, pH = 2, like lemon juice
- Formic acid had formed out of the glycol/water mixture (after warming up during the 2006 shutdown)
- Corrosion affected vulnerable parts (Al-alloys welding, brass e-valves)

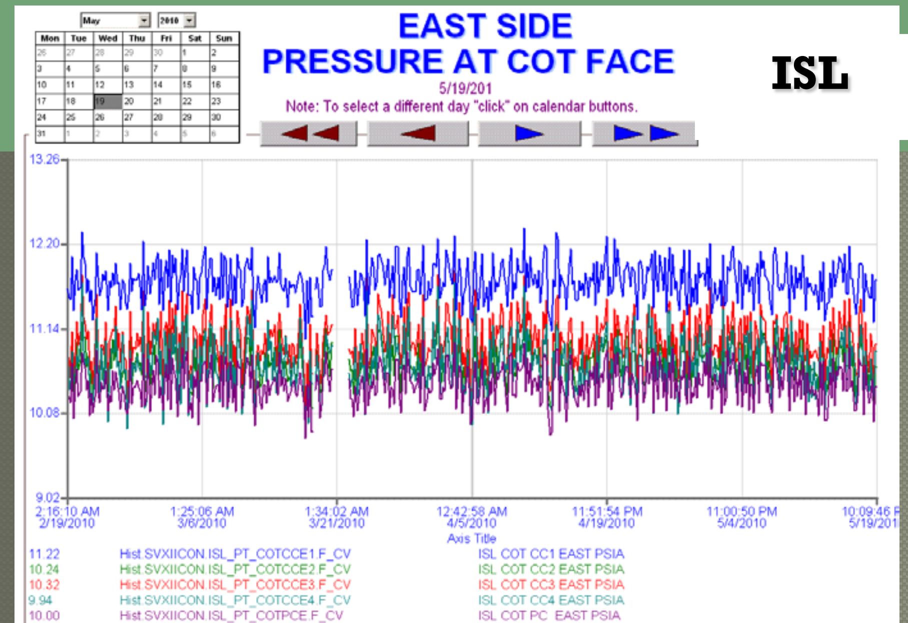


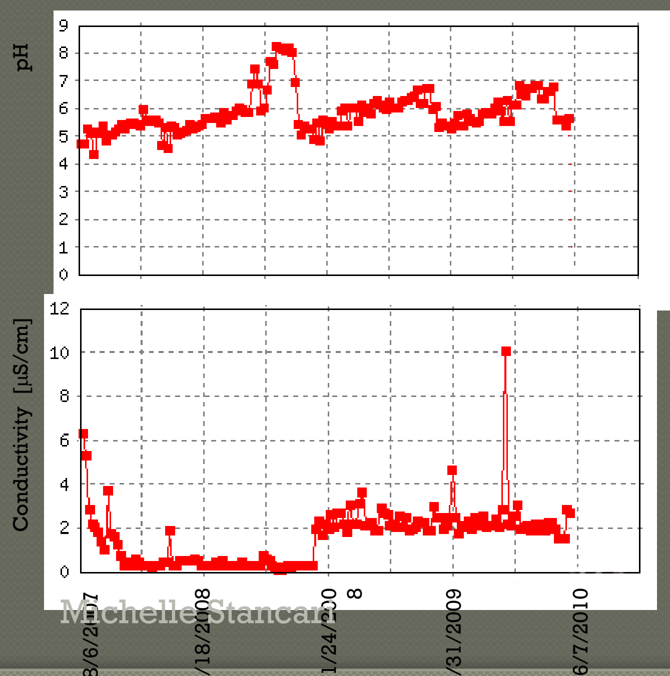
ISL Cooling System: The Saga of 2007

The Repair

- Internal walls of pipes were probed using boroscopes and catheters
  (~1 m inside CDF detector)
- Port Card manifold-pipe junctions were coated with epoxy
- Brass e-valves were replaced (mounted on CDF detector)
- The ISL coolant was replaced with deionized water
- Expanded monitoring of pH and conductivity
- Frequent replacement of deionizer (DI) resin filters





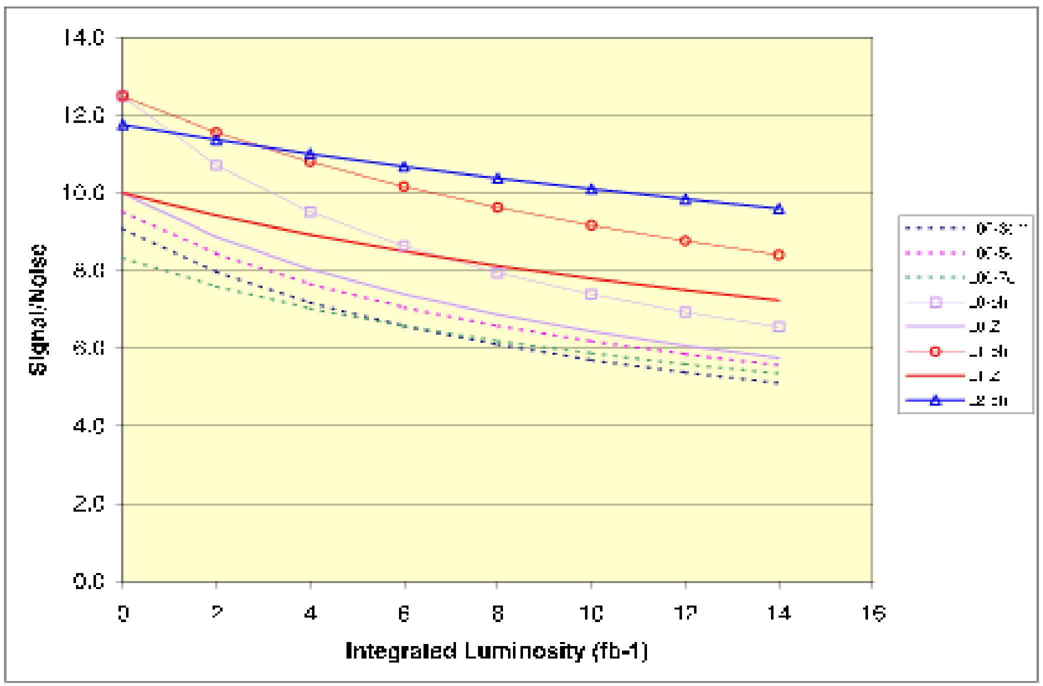


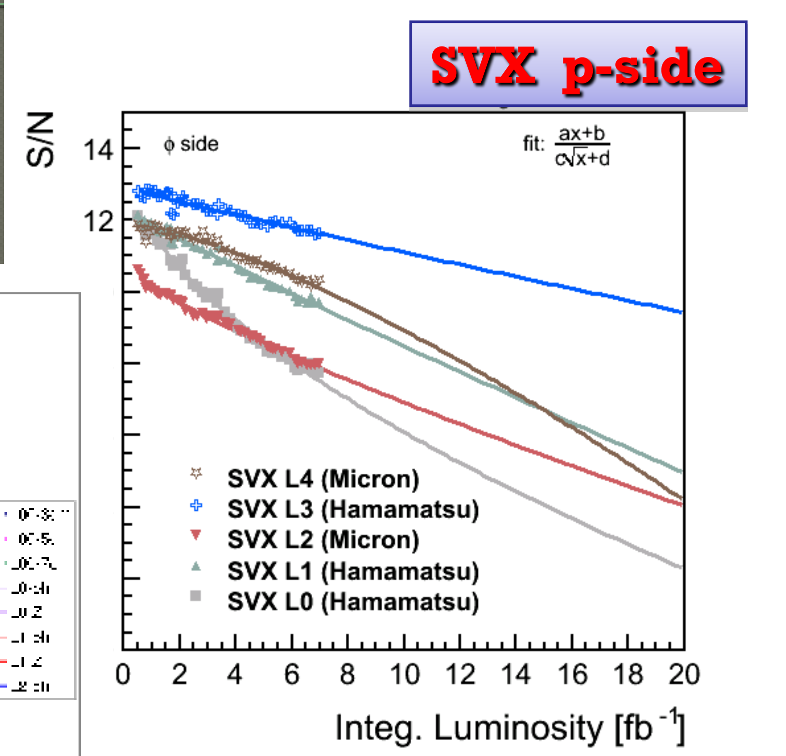
Current status of ISL Cooling

- Running, no serious incidents
- Good and stable flows
  - ISL CCE1 is stable but lower than perfect
- Good and stable sub-atmospheric pressures
- pH measured weekly from coolant samples
- Low conductivity <2 μS/cm
- Maintenance during each shutdown to improve hermeticity
- Chillers running well,
- New air-cooled backup chiller for power outages

Expected S/N

CDF note 6673 (2003)
S/N predictions assumed increase in noise and no change in signal





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

SVX3d chip

- Analog Front End and Digital Back End
  - Compatible with 396/132 nsec bunch spacing
  - FE has relatively low noise integrator with 128 channels and 46 cell analog pipeline with 4 buffer cells
  - BE has a comparator, 8-bit Wilkinson ADC, and sparse readout with nearest-neighbors
- Dead-timeless
  - Capable of analog operations during digitization and readout
- Dynamic Pedestal Subtraction
  - Enables on-chip common mode noise suppression
- Fabricated with Honeywell 0.8 μm rad hard process

SVX3d chip

Fabricated in the Honeywell 0.8μm rad.hard process