14th International Workshop on Vertex Detectors
Lake Chuzenji, Nikko, Japan, November 7 –11, 2005

Radiation Experience with the CDF Silicon Detectors

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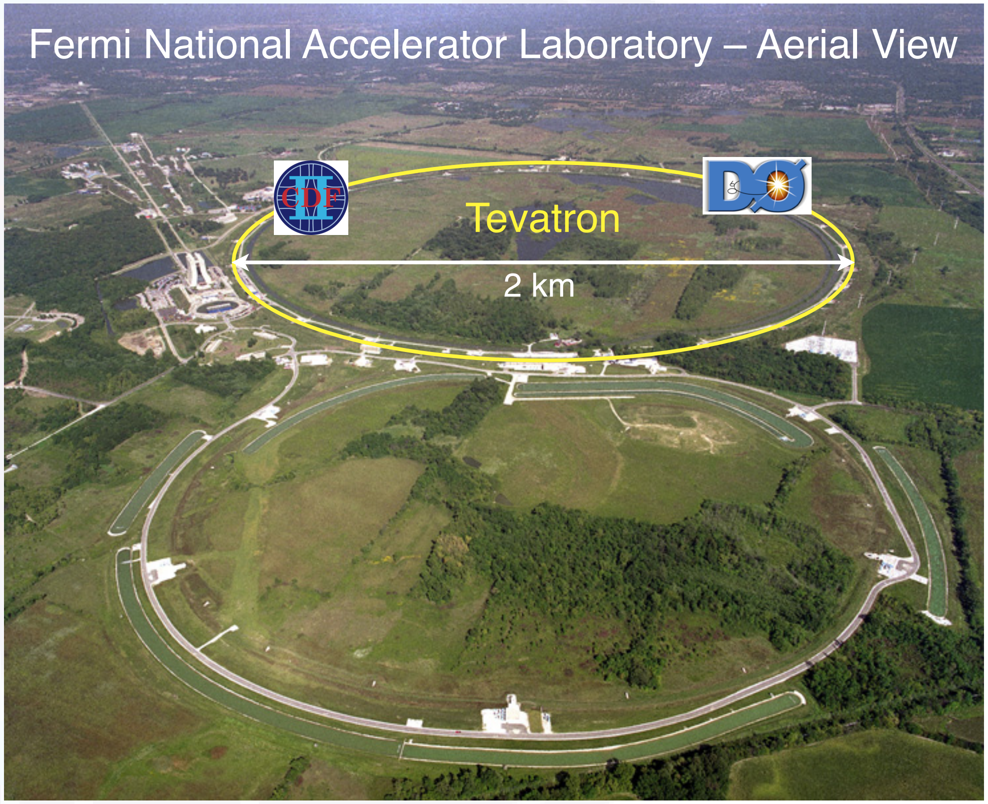
University of Rochester
on behalf of the
CDF Silicon and Radiation Monitoring Groups

The CDF-II Detector at the Tevatron

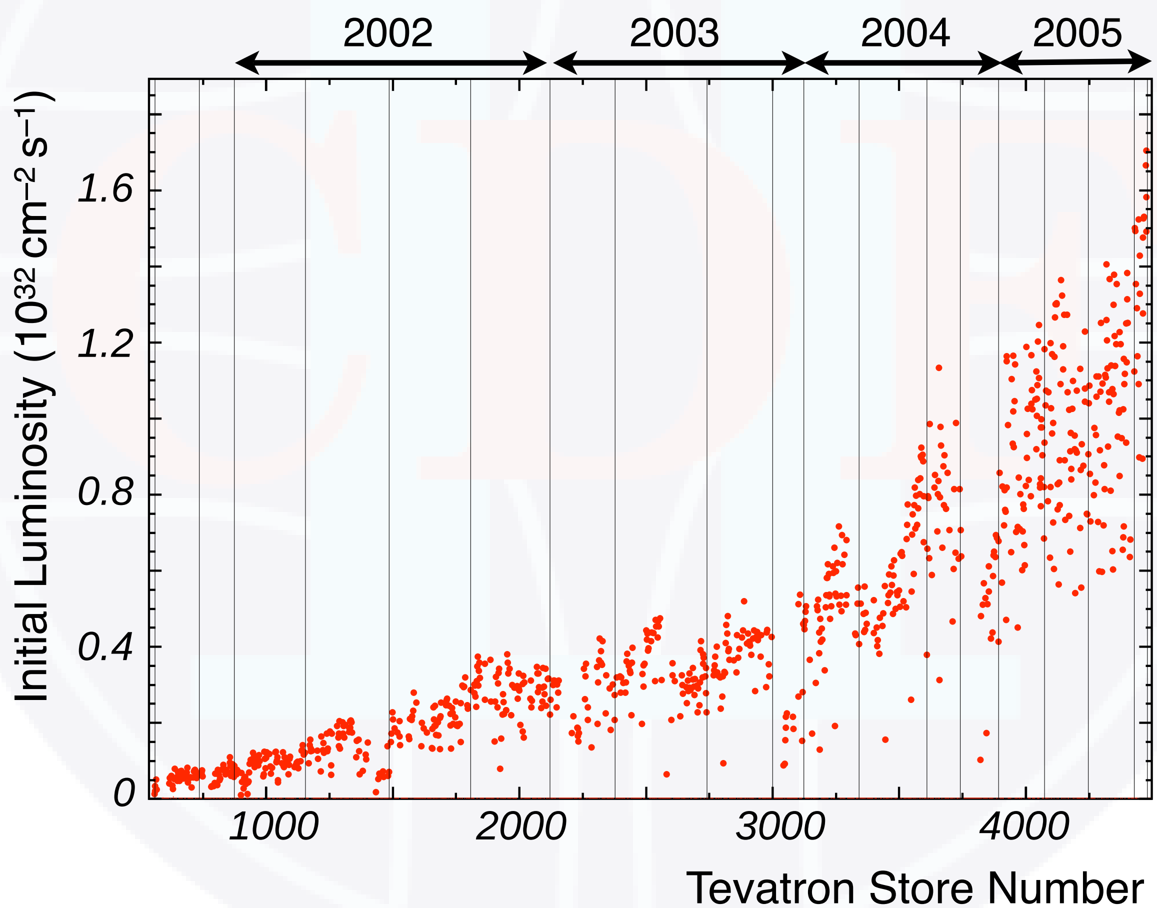
Tevatron Run II

- Proton-antiproton collider, $\sqrt{s}$ = 1.96 TeV
- 36×36 bunches
- Collisions every 396 ns
- Current instantaneous peak luminosity: > 1.5×10^{32} cm^{-2} s^{-1}
- Luminosity goals:
  - Instantaneous: (2–4)$\times10^{32}$ cm^{-2} s^{-1}
  - Integrated: 4–8 fb^{-1}
- Two multi-purpose experiments: CDF & D0



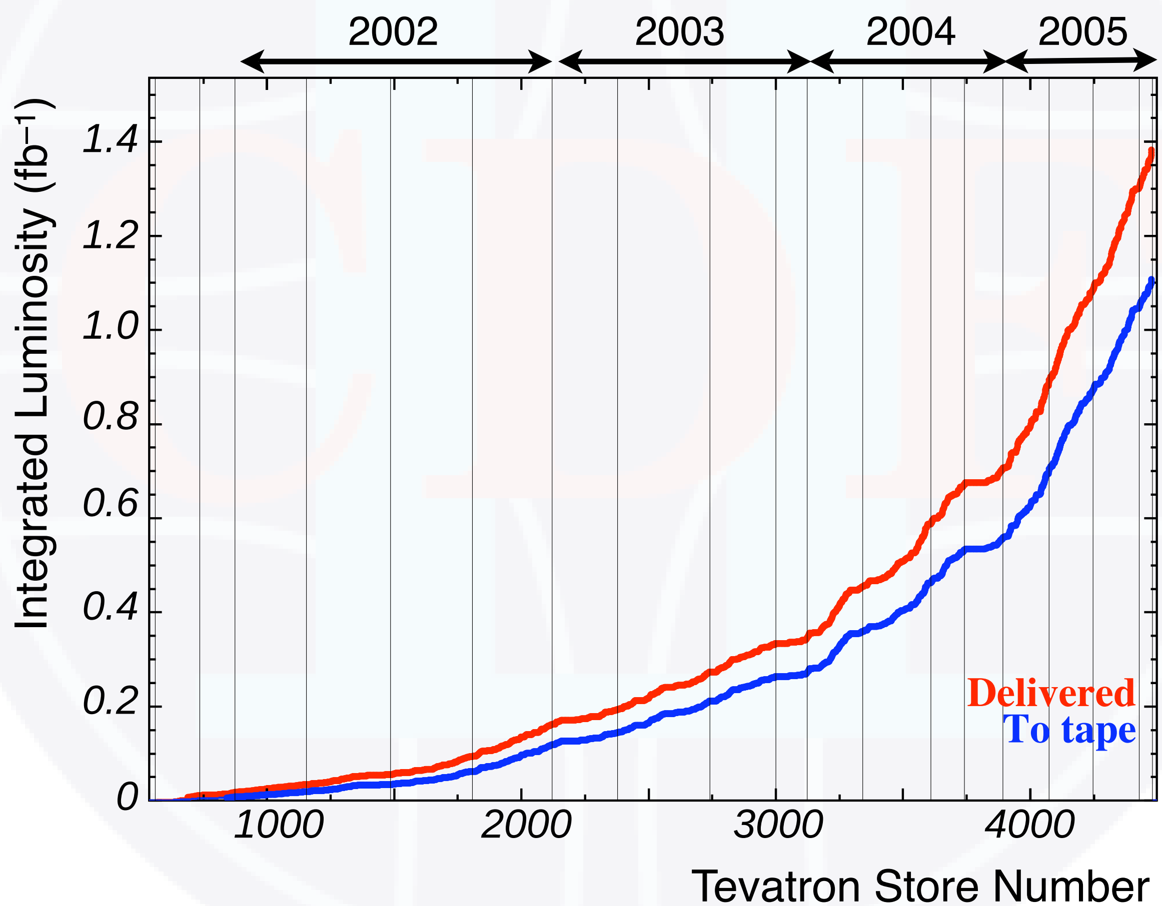
Tevatron Performance

- World record peak luminosity for hadron colliders: 1.64×10^{32} cm^{-2} s^{-1} (better than CERN ISR)

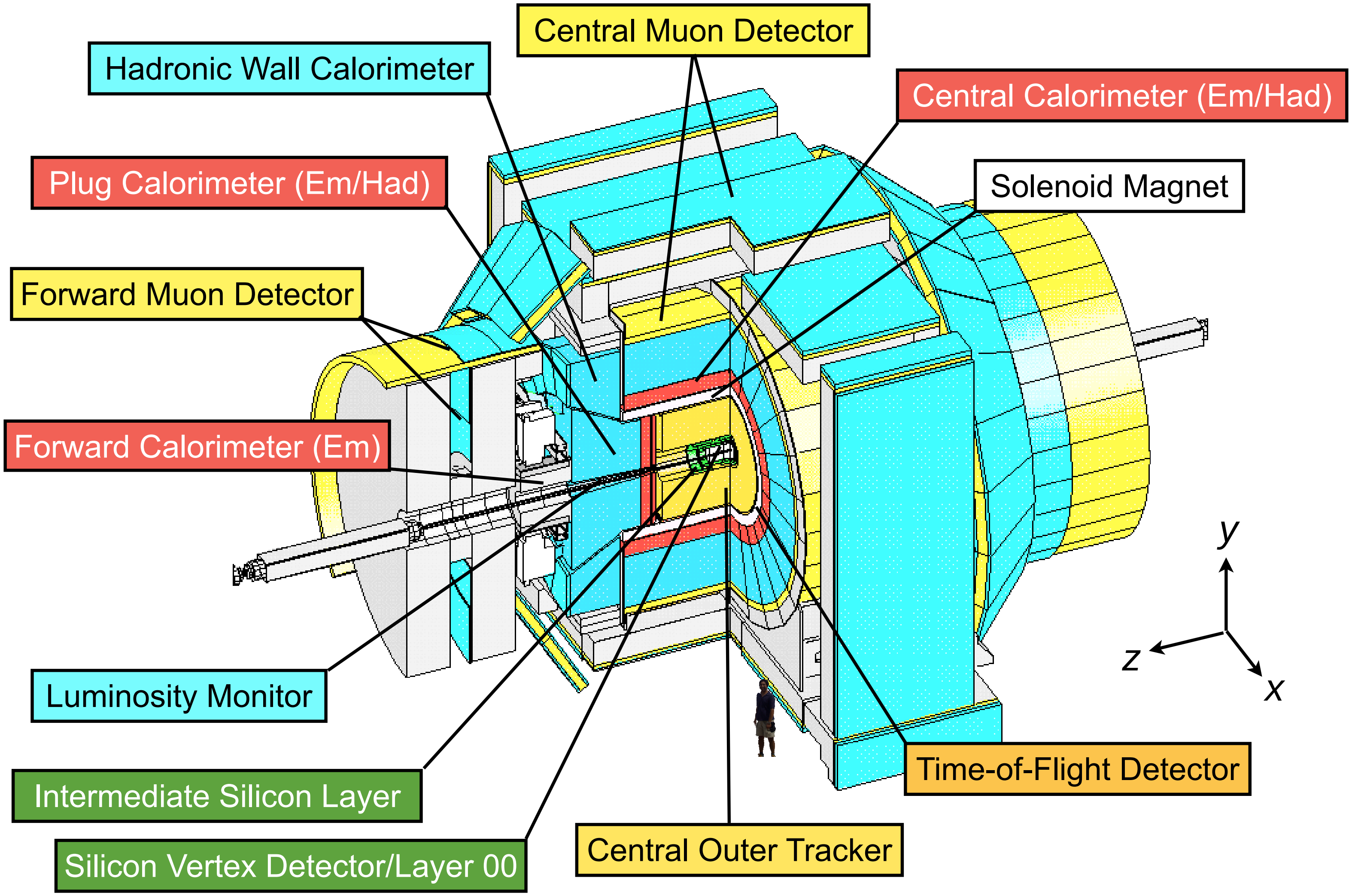


Integrated Luminosity

- CDF detectors have "seen" more than 1.4 fb^{-1} of integrated luminosity in Tevatron Run II

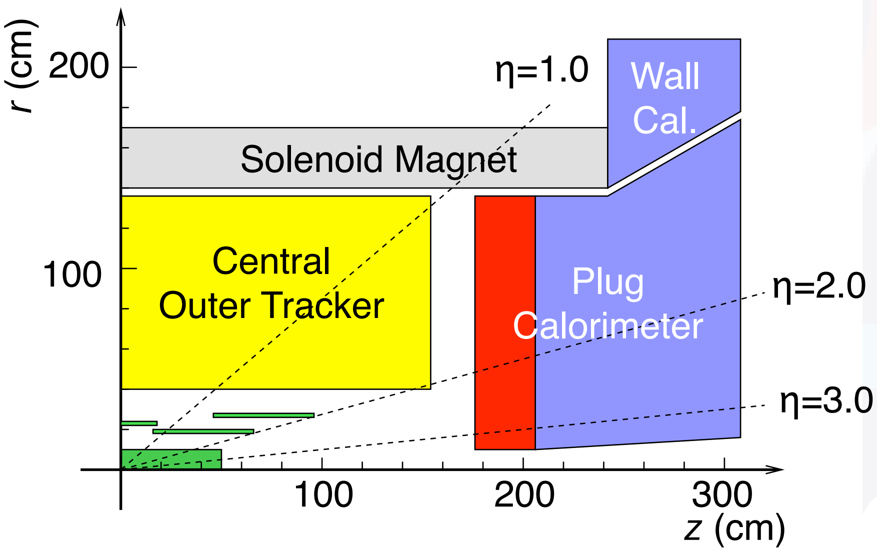


The CDF Detector



Silicon Detectors in CDF

- 7–8 silicon layers (6 m^2)
- 722k readout channels on 5.3k readout chips
- Designed to last for 2–3 fb^{-1} (SVX), must last for 4–8 fb^{-1}
- Quadrant of inner detectors:



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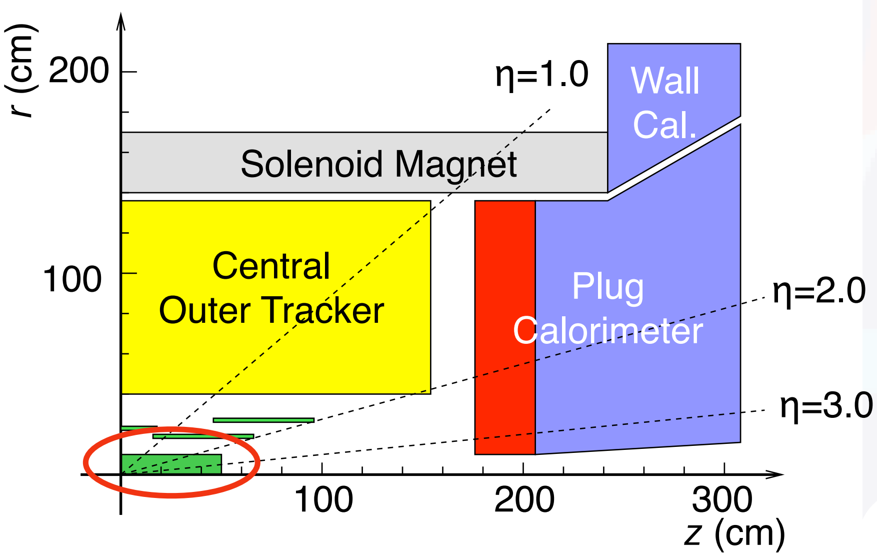
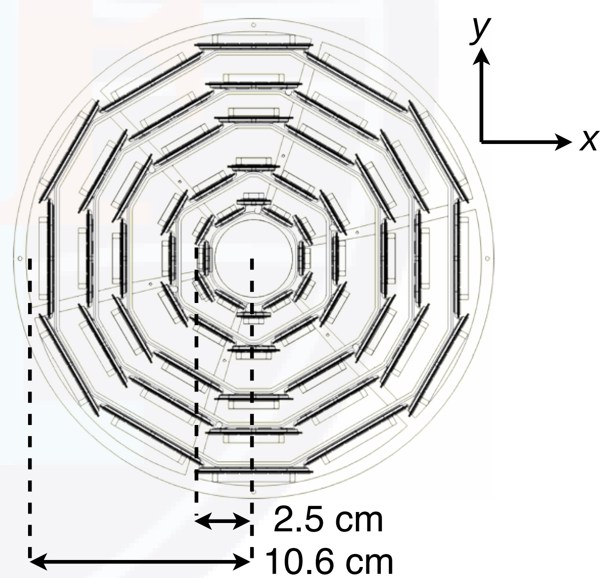


SVXII:
- 5 layers of double-sided sensors
- "Workhorse" for 3D tracking
- Secondary vertex trigger (see talk by R. Carosi)



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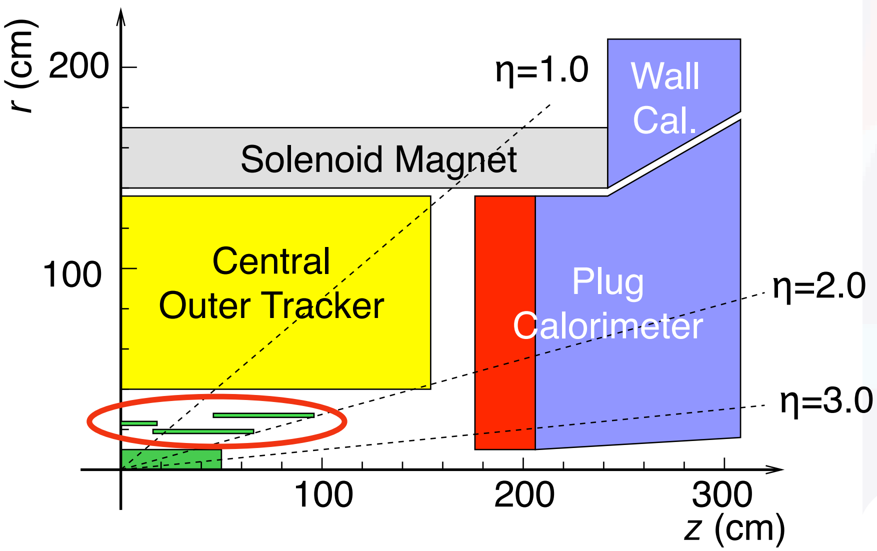
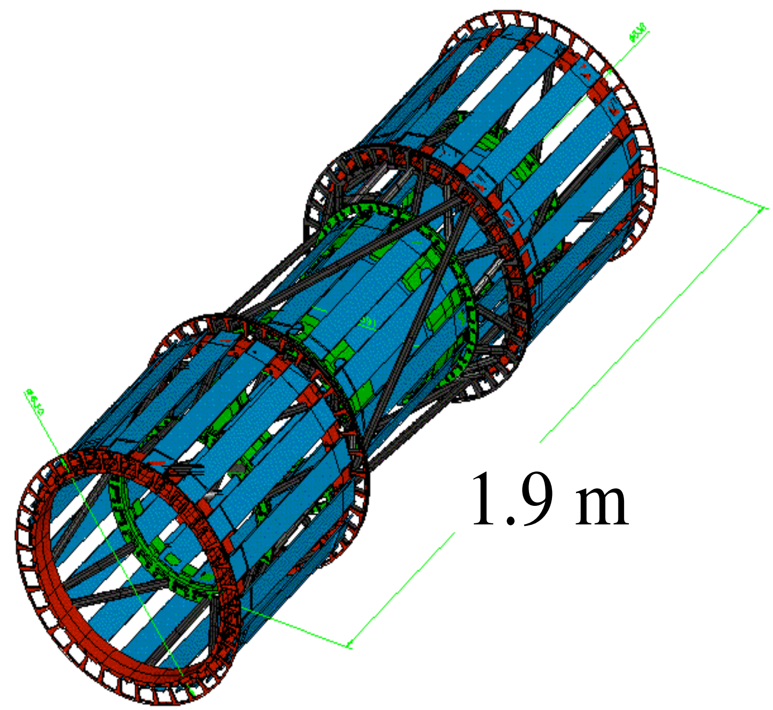


Intermediate Silicon Layer:
– Link SVXII and Central Outer Tracker
– Forward tracking to η=2



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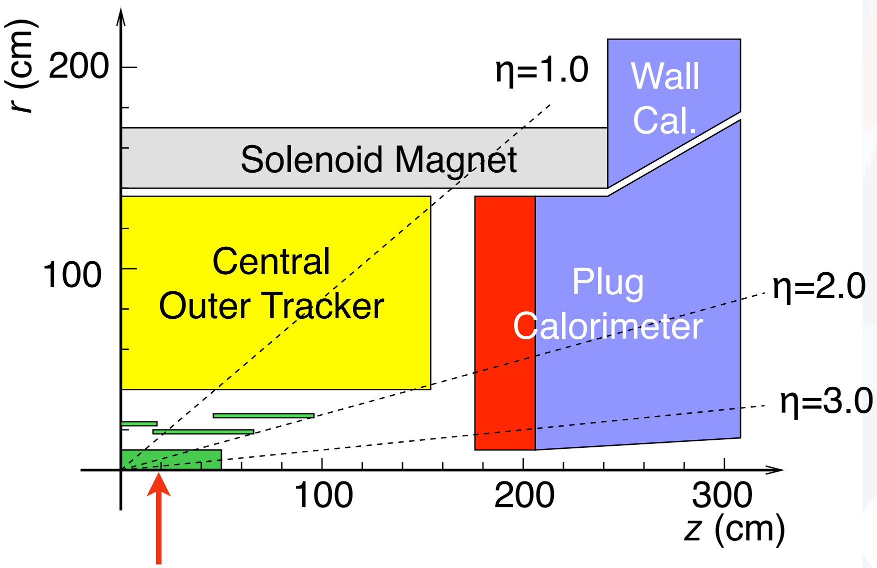
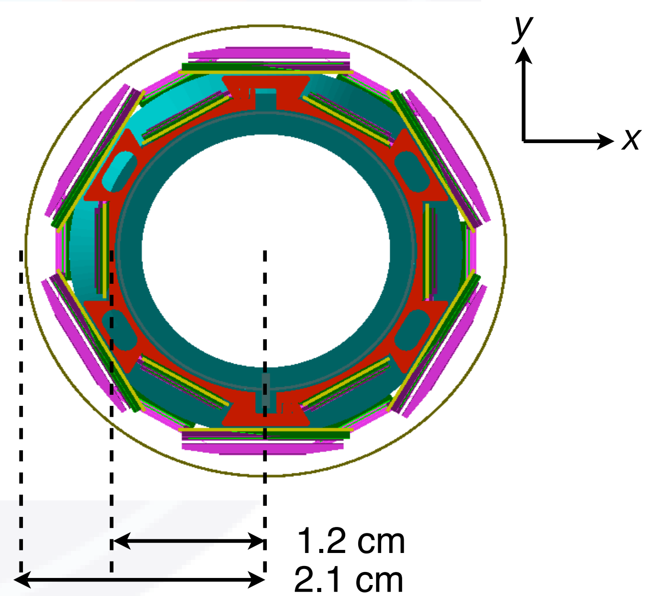


L00:
- LHC-like single-sided sensors, readout electronics separated from sensors
- Mounted on beam pipe: precision tracking point before scattering in detector



Motivation

- Main objectives of CDF Silicon Operations group:
  - Ensure stable and safe operation of silicon detectors
  - Keep silicon detectors alive through Tevatron Run II
  - Record good physics data at high efficiency
- Focus of CDF Radiation Monitoring group:
  - Measure and monitor radiation near silicon detectors and electronics
  - Evaluate radiation damage
- This talk will focus on two aspects of silicon lifetime:
  - Beam-related incidents:
    single-event upsets, abort kicker “prefire”
  - Assessment of radiation damage:
    monitoring of bias currents and depletion voltages

Beam-Related Incidents

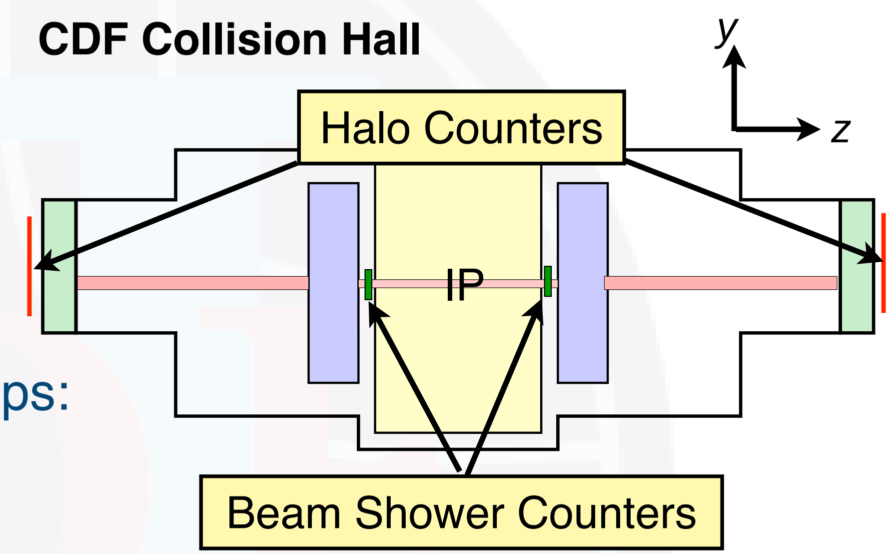
Beam Incidents

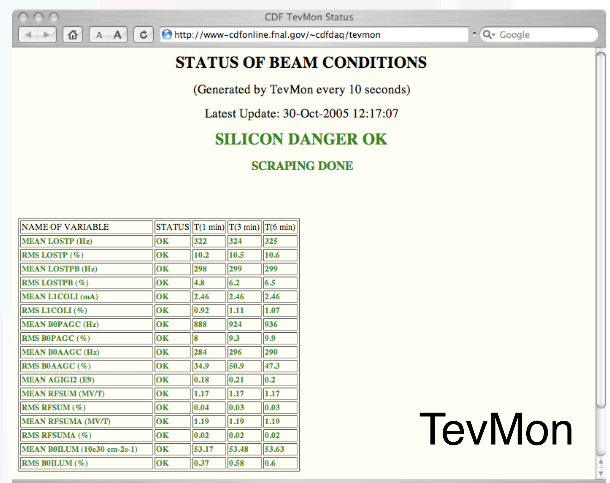
- Tevatron:
  - Most powerful $p\bar{p}$ collider to date
  - Kinetic energy of beams equivalent of a race car at 200 km/h
- Beam incidents: major concern for longevity of silicon detectors
- Most dangerous incidents:
  - Magnet quench due to beam losses
  - Abort kicker “prefire”


Beam incident in Tevatron collimator

Monitoring the Tevatron Beam

- Continuous redundant monitoring of beam parameters by Radiation Monitoring group and Tevatron group:
  - Beam losses and abort gaps: Halo counters and beam shower counters (BSC)
  - Abort gaps: electron lens
  - RF power, etc.
- TevMon: tool for shift crew
  - Automatic evaluation of beam parameters
  - Crew ramps down bias voltages under “dangerous” beam conditions





CDF TevMon Status

STATUS OF BEAM CONDITIONS

(Generated by TevMon every 10 seconds)

Latest Update: 30-Oct-2005 12:17:07

SILICON DANGER OK

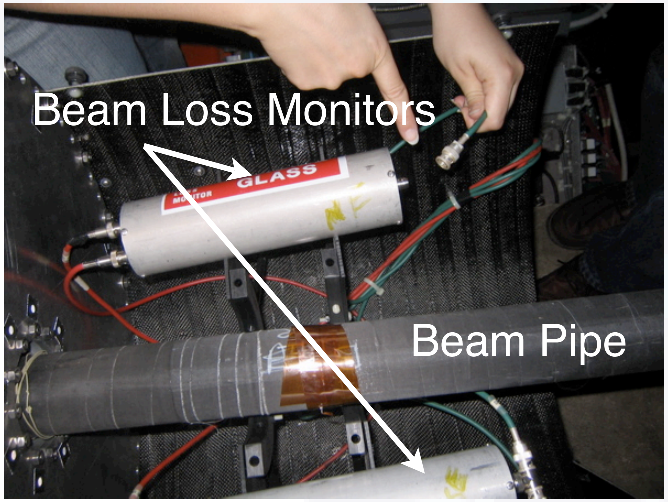
SCRAPING DONE

NAME OF VARIABLE	STATUS	T(1 min)	T(3 min)	T(6 min)
MEAN LOSTP (Hz)	OK	322	324	325
RMS LOSTP (%)	OK	10.2	10.5	10.6
MEAN LOSTPB (Hz)	OK	298	299	299
RMS LOSTPB (%)	OK	4.8	6.2	6.5
MEAN L1COLI (mA)	OK	2.46	2.46	2.46
RMS L1COLI (%)	OK	0.92	1.11	1.07
MEAN B0PAGC (Hz)	OK	888	924	936
RMS B0PAGC (%)	OK	8	9.3	9.9
MEAN B0AAGC (Hz)	OK	284	296	290
RMS B0AAGC (%)	OK	34.9	50.9	47.3
MEAN AGIGI2 (E9)	OK	0.18	0.21	0.2
MEAN RFSUM (MV/T)	OK	1.17	1.17	1.17
RMS RFSUM (%)	OK	0.04	0.03	0.03
MEAN RFSUMA (MV/T)	OK	1.19	1.19	1.19
RMS RFSUMA (%)	OK	0.02	0.02	0.02
MEAN B0ILUM (10e30 cm-2s-1)	OK	53.17	53.48	53.63
RMS B0ILUM (%)	OK	0.37	0.58	0.6

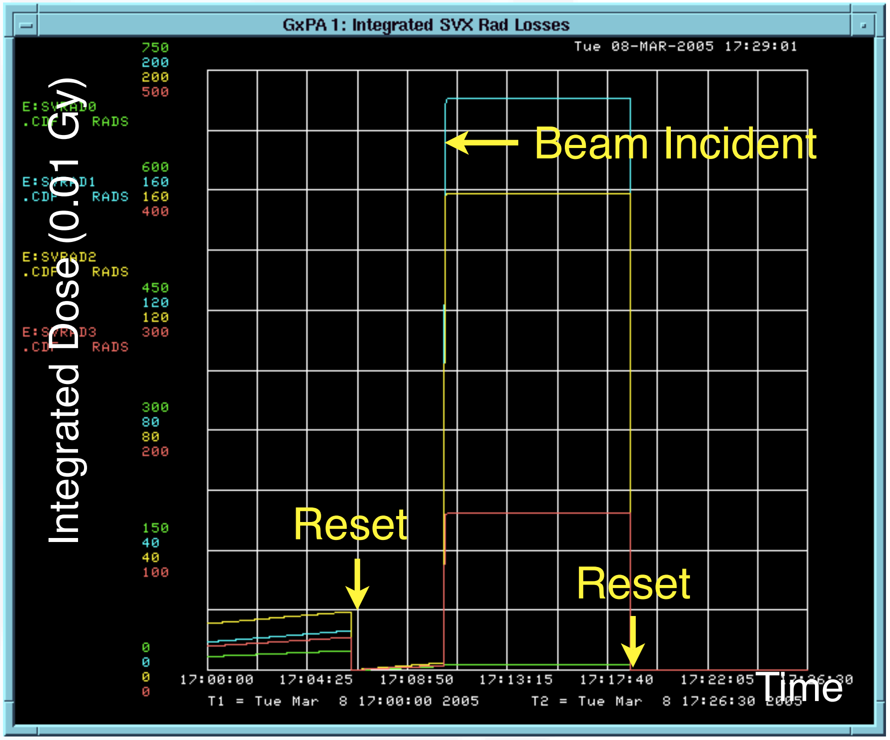
TevMon

Aborting the Tevatron Beam

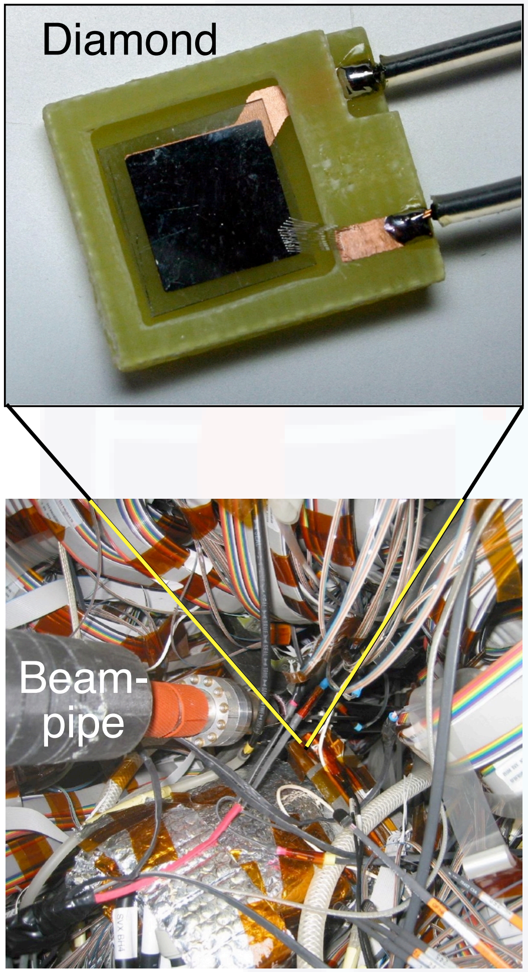
- Monitoring of instantaneous and integrated dose rate by four Beam Loss Monitors (BLM)
- CAMAC logic triggers beam abort if dose rate exceeds 0.12 Gy/s



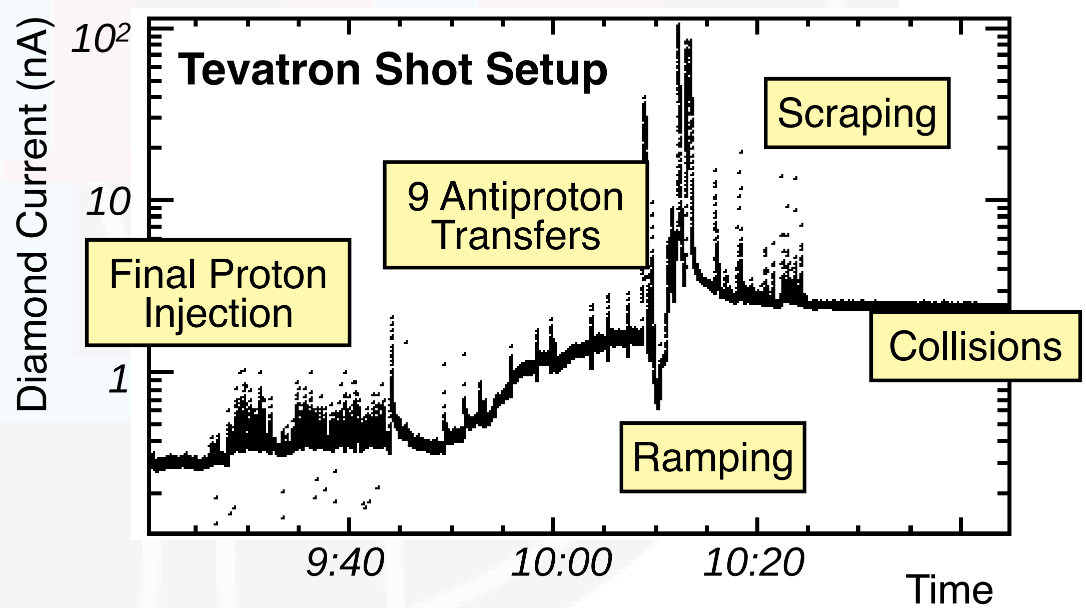
BLMs: Integrated Dose



Prototype Diamond Detector

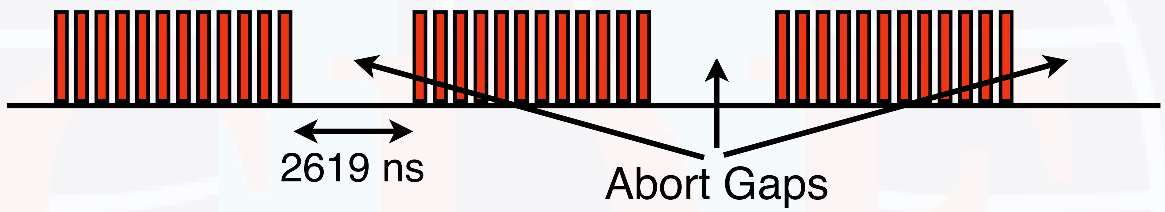


- Prototype system: signal currents in diamond detectors
  - Installed October ‘04
  - Can be used both for beam monitoring and abort

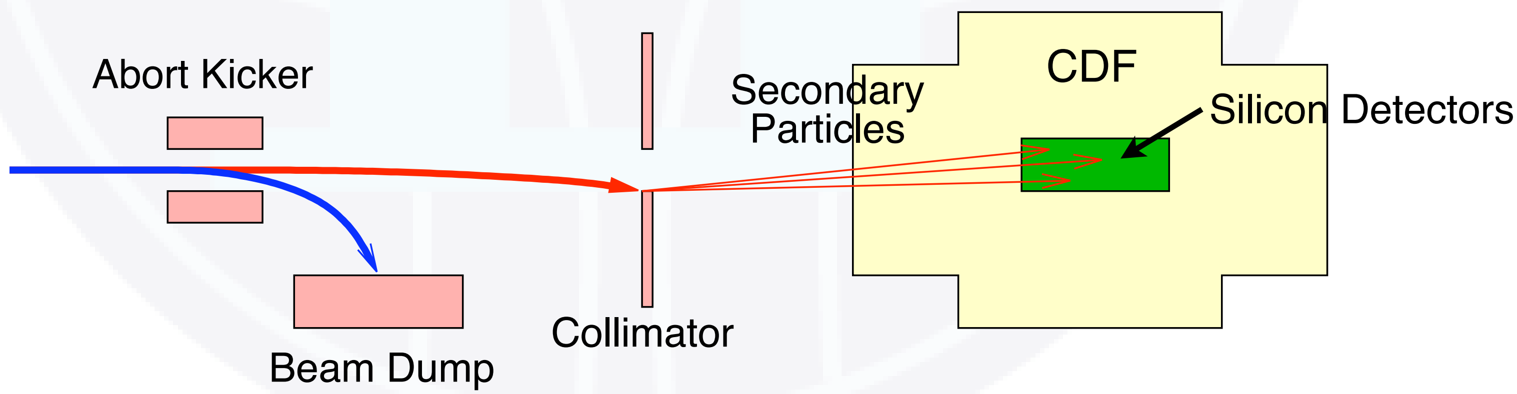


Abort Kicker Prefire

- Tevatron beam abort:
  - Bunch structure: 3×12 bunches, interleaved with "abort gaps"

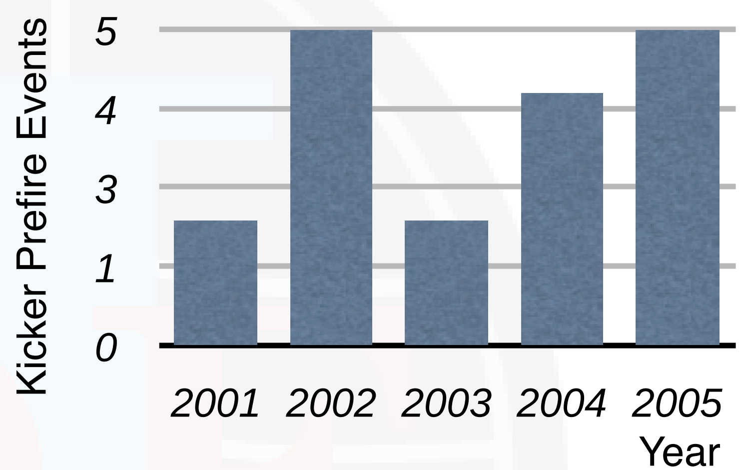


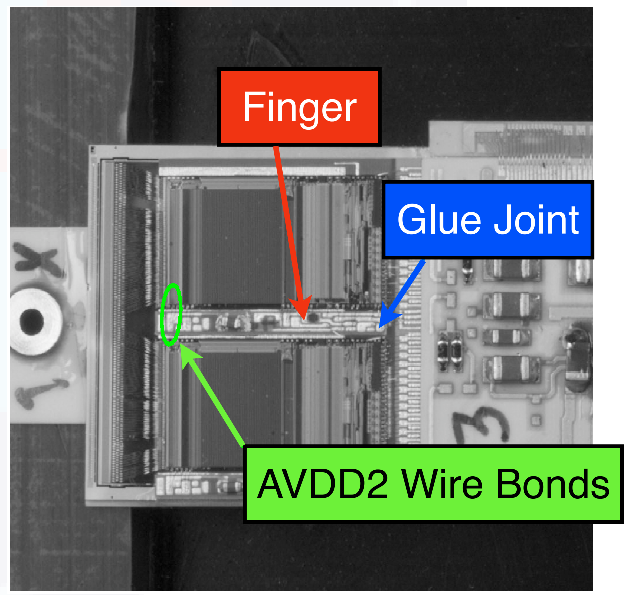
  - 2×5 kicker magnets to abort beam: ramped in abort gaps
- Kicker "prefire": spontaneous ramping of kicker magnets → beam sprayed into CDF silicon detector



Failure of Analog Power Line

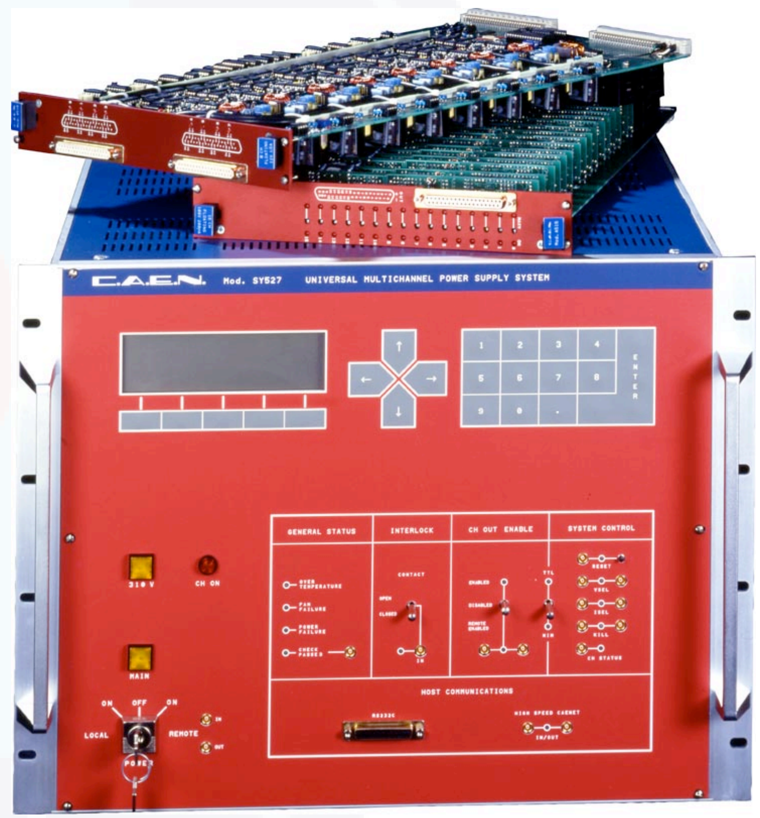
- Kicker prefires are rare (18 so far in Run II), but potentially dangerous, mostly for SVX readout chips:
  - All chips in a silicon ladder are daisy-chained in the readout
  - Observe drop in analog current, all chips in chain following compromised chip are lost
  - Conjecture: Failure due to broken silver epoxy glue joint (not yet reproduced in laboratory and test beam)





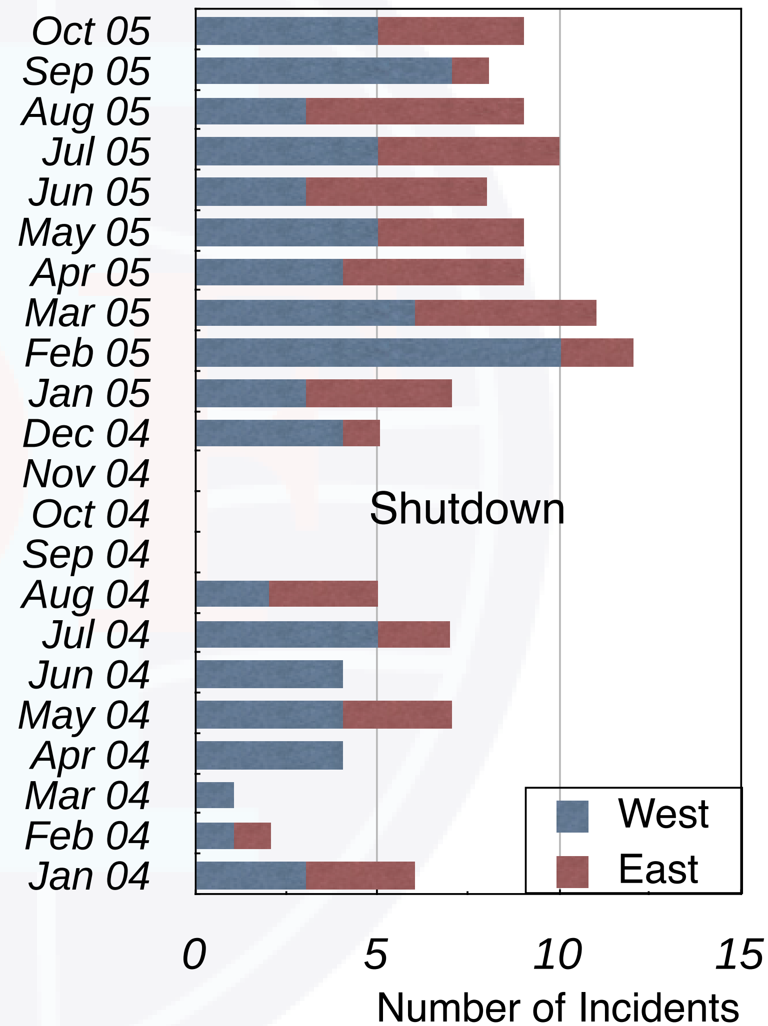
Power Supply Problems (I)

- Silicon detectors powered by 114 custom power supplies in CAEN SY527 mainframes
- Power supplies mounted in racks in CDF collision hall, controlled remotely by CAENnet bus
- Common failure modes of power supplies:
  - Spontaneous switch-off
  - Loss of CAENnet communication
  - Corrupted read-back of currents/voltages



Power Supply Problems (II)

- Problems are most probably beam-related:
  - Failure rate increases with increasing luminosity
  - Crates in areas with higher radiation dose are more likely to fail
- Short-term fix: reboot (“Hockerize™”) crate CPU
- Working with CAEN to better understand (and possibly fix) the problem



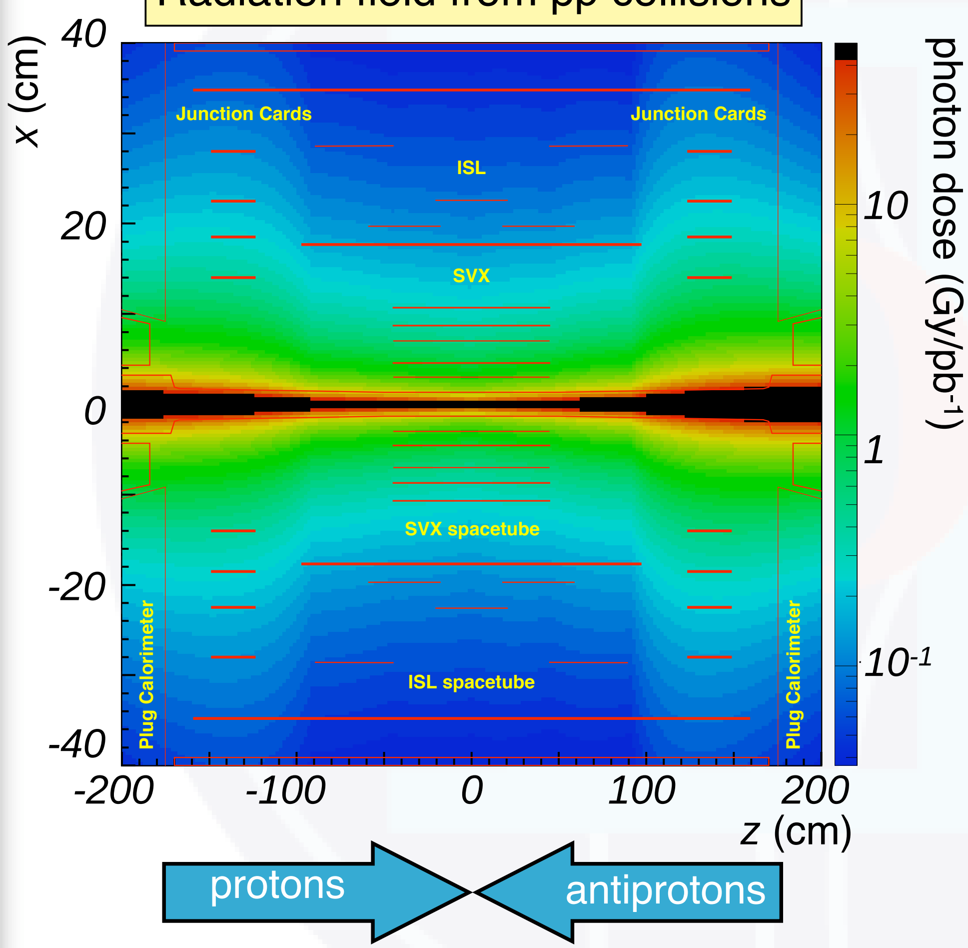
Radiation Measurements

Radiation Monitoring

- Monitoring of radiation damage
  - CDF Radiation Monitoring Group:
    Dose of ionizing radiation in tracking volume (TLDs, *I*-*V* curves of PIN diodes) and thermal neutrons (TLDs)
  - Bias currents: continuously monitored during beam time
  - Depletion voltage: scans of signal and noise vs. bias voltage in specialized data-taking runs
- Two main concerns for silicon longevity:
  - Acceptable signal-to-noise during entire Tevatron Run II?
    → study chip noise and increase in sensor bias currents
  - Type inversion in silicon sensors: can we fully deplete the silicon sensors during the entire Tevatron Run II?
    → study depletion voltage

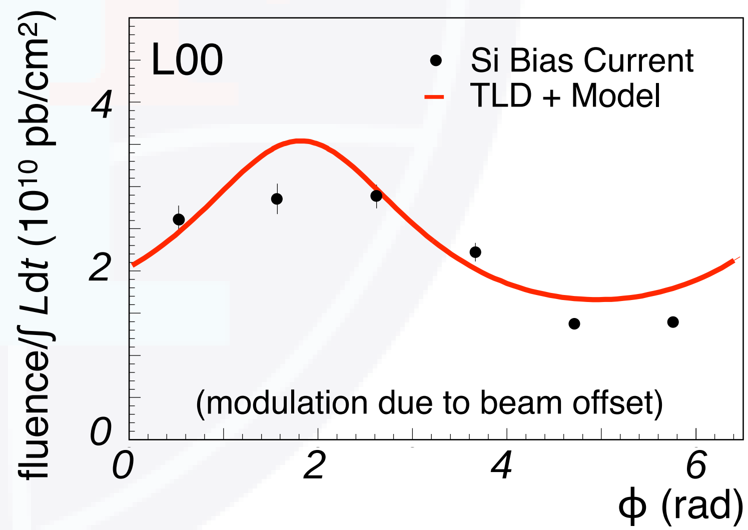
Radiation Monitoring

Radiation field from p$\bar{p}$ collisions



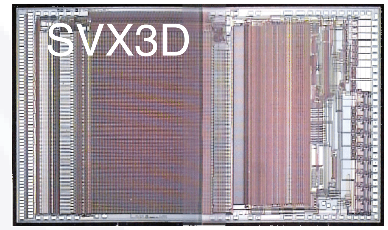
R. J. Tesarek *et al.*, IEEE NSS 2003

- Radiation field measured by >1000 TLDs in tracking volume
- Agreement between bias current measurement and extrapolated TLD measurement: 10%

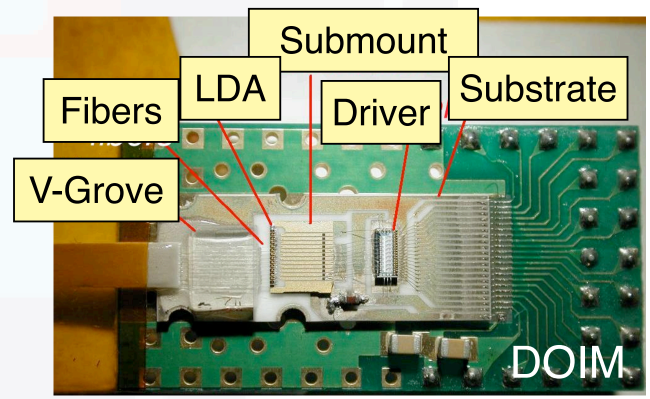


Radiation Hardness of Electronics

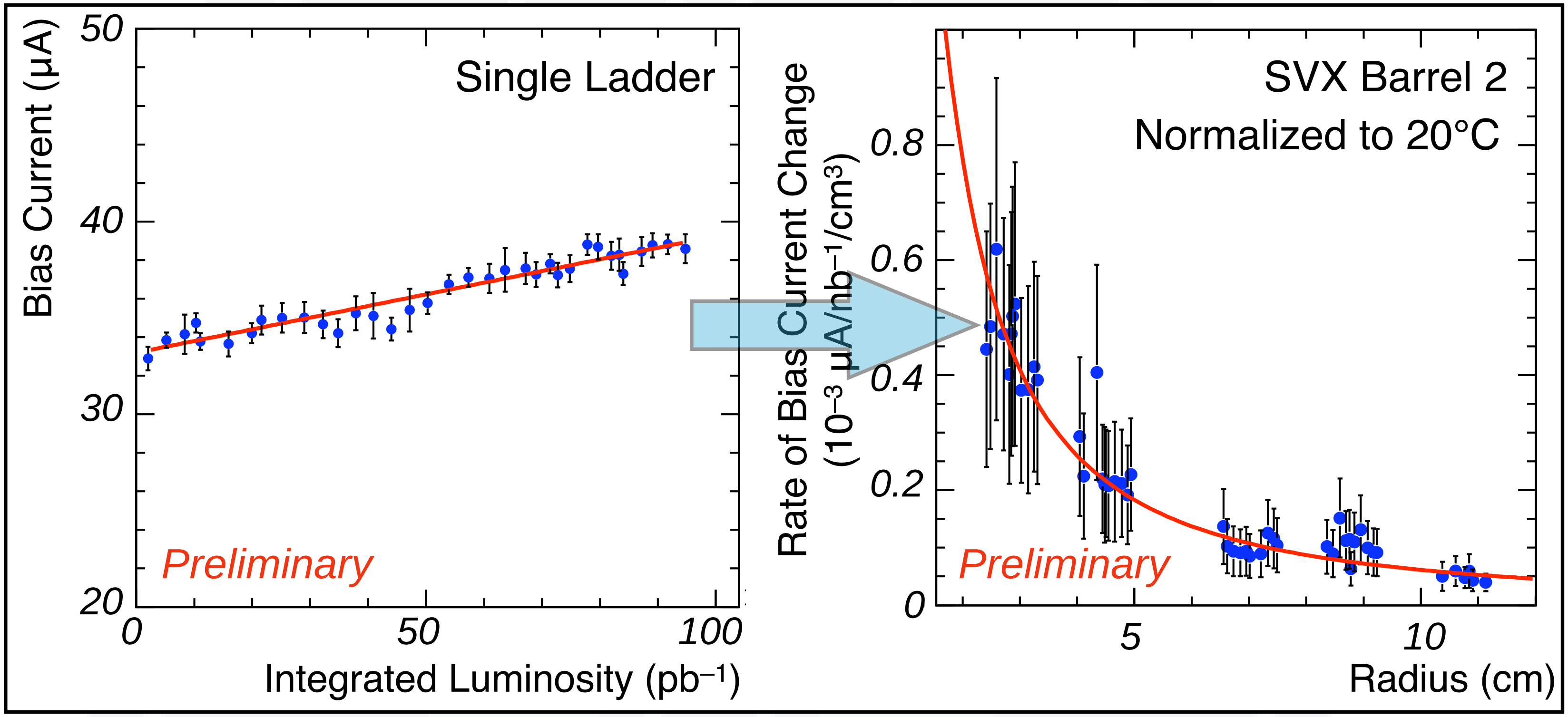
- Silicon readout chip (“SVX3D”):
  - Produced in radiation-hard CMOS process
  - SVX Layer 0: chips closest to interaction point, r = 2.5 cm
  - Radiation tests with ^{60}Co source and 55 MeV protons
  - Increase of chip noise after 8 fb^{-1} (40 kGy): 17% for innermost SVX layer



- Optical transmitter (“DOIM”):
  - Mounted on “portcards” outside SVX tracking volume, r > 10 cm
  - Radiation-hard to 2 kGy, expect 1.4 kGy in 8 fb^{-1}
  - 8 fb^{-1}: 10% degradation of light level, no change in waveform

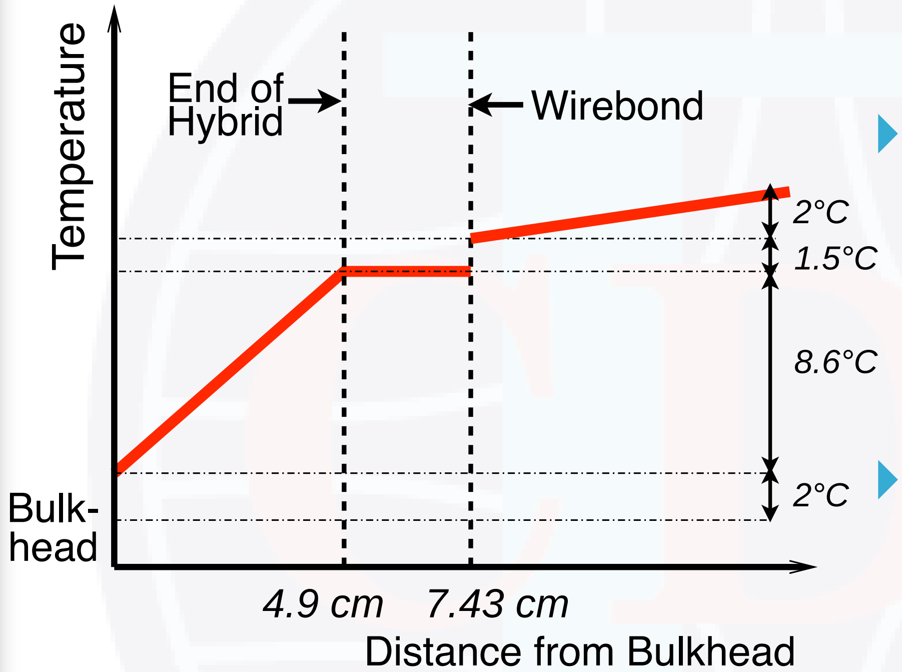


Bias Currents



- Linear increase of bias current with luminosity
- Radial dependence of slope: large systematic uncertainties from temperature model

Temperature Model



$$\frac{I_2}{I_1} = \left(\frac{T_2}{T_1}\right)^2 \exp\left[-\frac{E_{gap}}{2k_B}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$

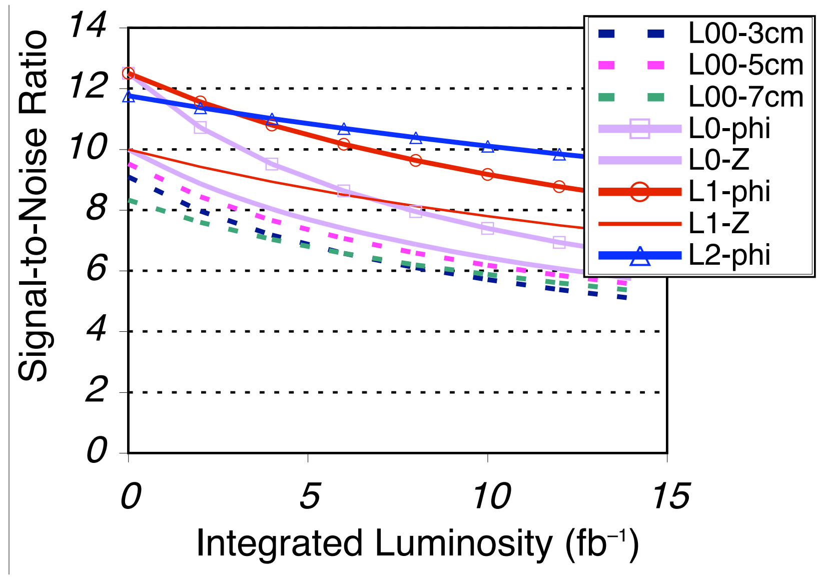
- Convention: normalize bias currents to 20°C
- SVX: temperature sensors (RTDs) mounted on support structure (“bulkhead”): no direct measurement on silicon sensor, need extrapolation
- Temperature extrapolation relies on early finite element analysis for sensor temperature: large systematic uncertainties of temperature correction factor (13%)
- Lesson learned: good monitoring of sensor temperatures is essential

Signal-to-Noise Ratio

- Limitation: secondary vertex trigger requires S/N > 6–8
- Assuming full depletion of silicon sensors:
  - Chip noise increase linearly with luminosity, 17% at 8 fb^{-1}
  - Shot noise of sensors related to leakage current:

    $$Q = 900e \times \sqrt{I_{\text{leakage}}[\mu\text{A}]}$$

    → dominant noise source

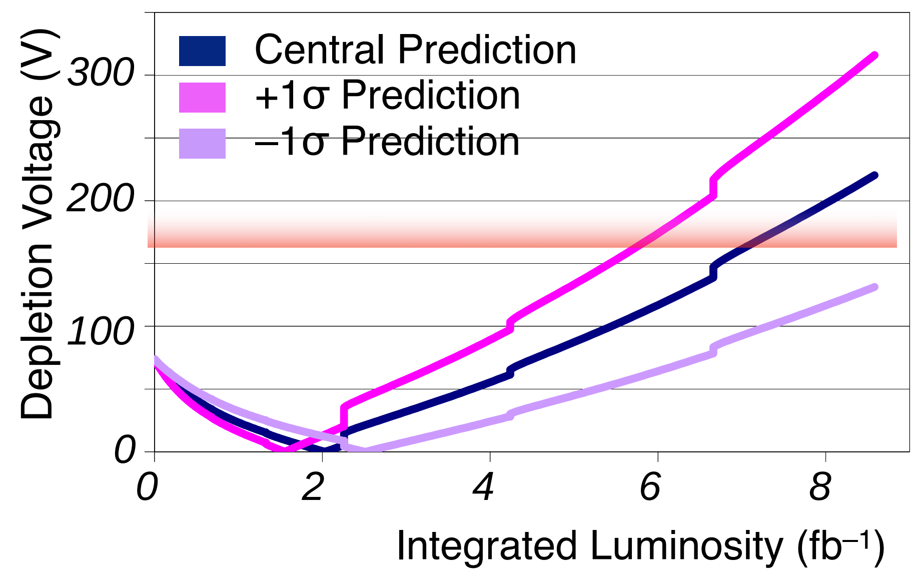


S. Worm, *Lifetime of the CDF Run II Silicon*, VERTEX 2003

- Bias current studies: first step towards update of 2003 result
  - More sophisticated analysis
  - Improved understanding of systematics

Depletion Voltage

- Type inversion causes evolution of bias voltage
- SVX: AC-coupled readout
  - Breakdown of capacitors limits depletion voltage
  - Hamamatsu sensors: $V_{\mathrm{dep,max}} \approx 170$ V
  - Micron sensors: $V_{\mathrm{dep,max}} \approx 60$ V
- L00: $V_{\mathrm{dep,max}} \approx 500$ V



S. Worm, *Lifetime of the CDF Run II Silicon*, VERTEX 2003

Predictions based on Hamburg model: $\Delta V_{\mathrm{dep}} \propto \Delta N_{\mathrm{eff}} = N_A + N_C + N_Y$

$$N_A = \Phi \sum_i g_{0,i} \exp[-c_{A,i}(T)\,t]$$ Beneficial Annealing

$$N_C = N_{C,0}\,(1 - \exp[-c\Phi]) + g_c\Phi$$ Stable Component

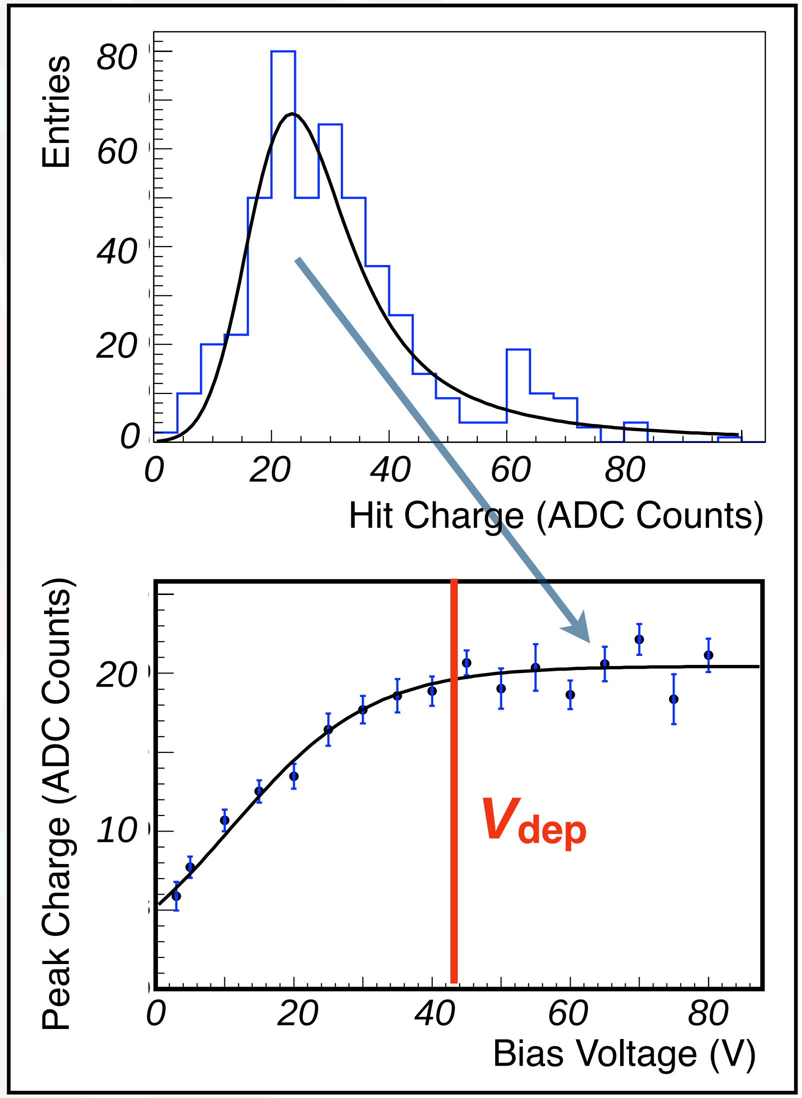
$$N_Y = g_Y \Phi \left(1 - \frac{1}{1 + g_Y \Phi c_Y(T)\,t}\right)$$ Reverse Annealing

Silicon Longevity Measures

- SVX temperature reduced (Spring 2005):
  - Temperature set-point: –6°C → –8°C → –10°C
  - Reduction of noise, mitigation of reverse annealing
- Silicon detector volume thermally isolated by “baggy”
  - Minimize thermo-cycles of detectors
  - Volume flushed with nitrogen: avoid condensation
- Measure depletion voltage in regular bias scans
  - Compare depletion voltage model (rather large uncertainties) with measurement
  - Straight-line extrapolations of point of type inversion and expected silicon lifetime

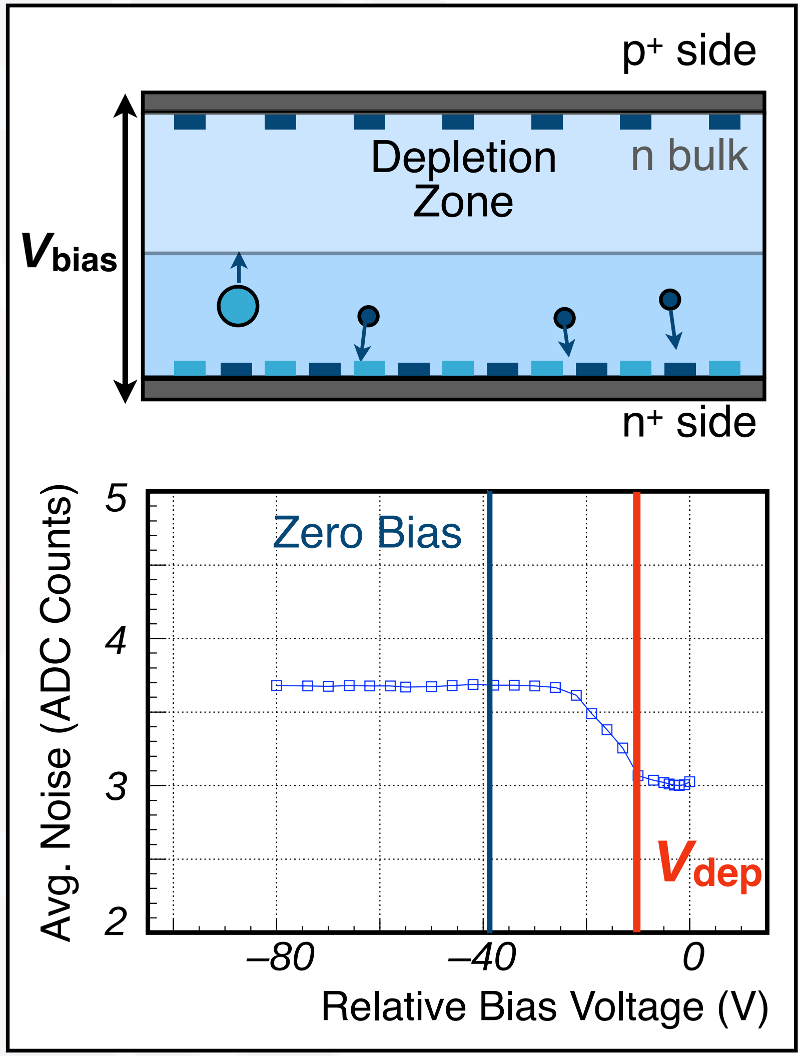
Method 1: Signal vs. Bias

- Study collected charge of silicon hits during colliding beams operation
- Find peak of ADC spectrum as a function of bias voltage (fit: Landau ⊗ Gaussian)
- Determine V_{dep} as 95% amplitude of sigmoid fit



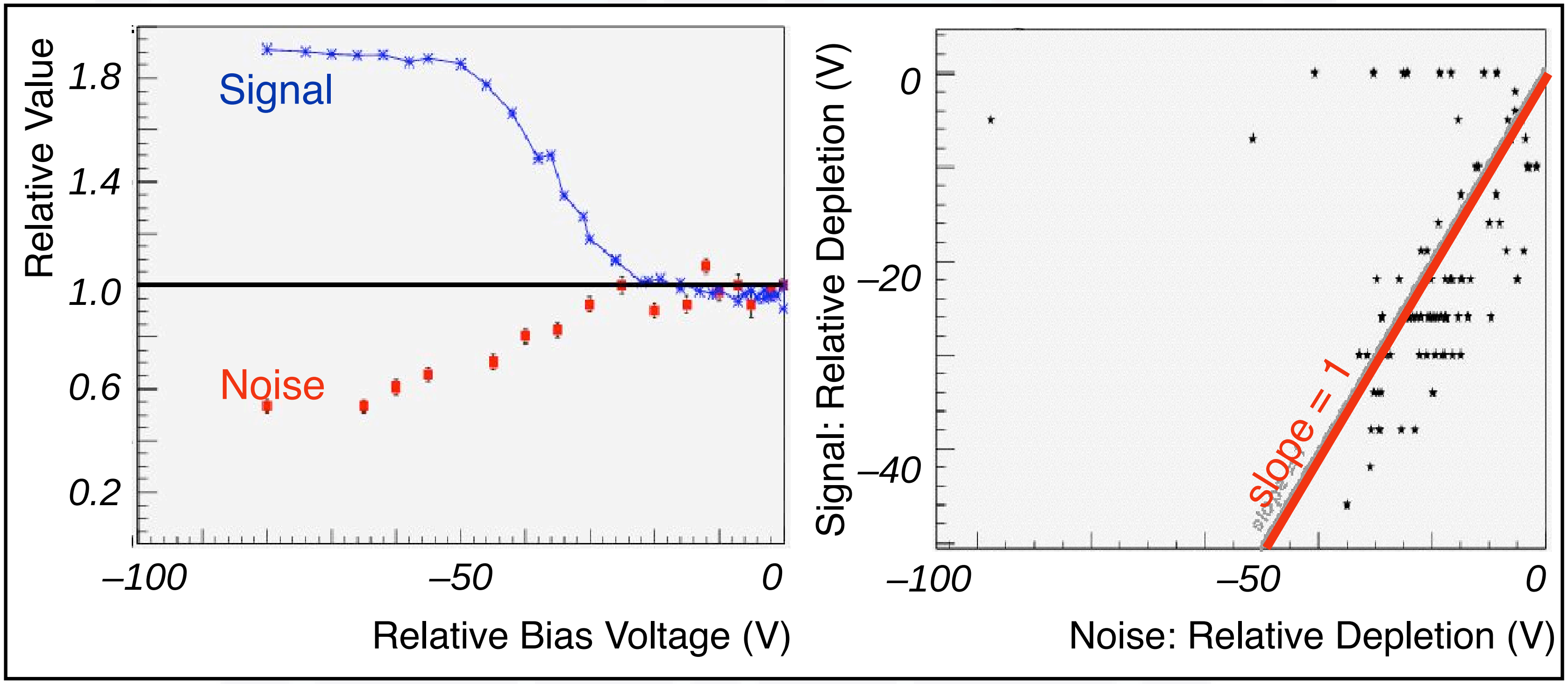
Method 2: Noise vs. Bias

- Measurement idea: inter-strip thermal noise on n side cleared by applying bias voltage
  → depleted detector has lower noise level
- Works only for double-sided sensors (i.e. SVX)
- Study average noise as a function of bias voltage
- Advantage: bias scan performed with no beam in accelerator
  → no interference with data-taking



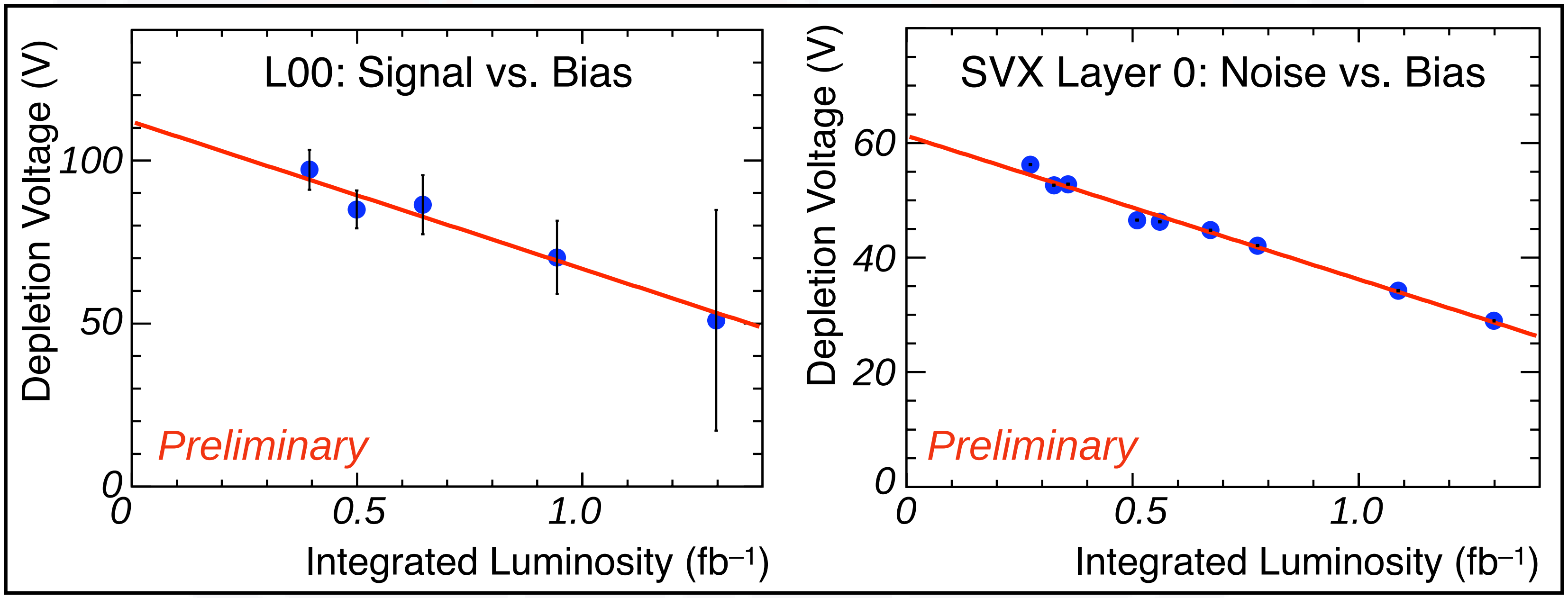
Comparing Bias Scan Methods

- Consistent result of signal and noise methods:



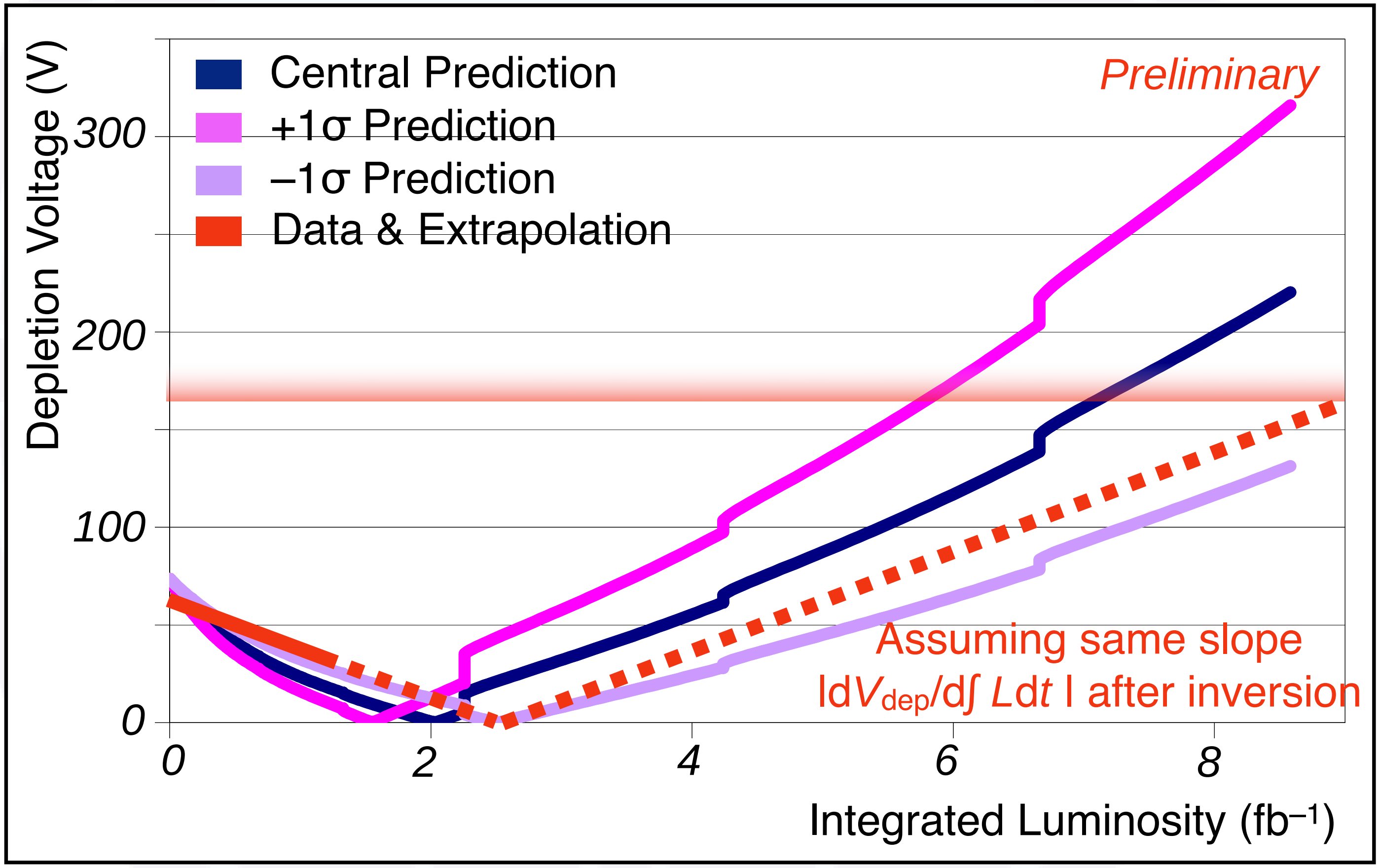
Depletion Voltage: Examples

- Straight-line fits to depletion voltages for single ladders: no indication for type inversion so far



Depletion Voltage: SVX Layer 0

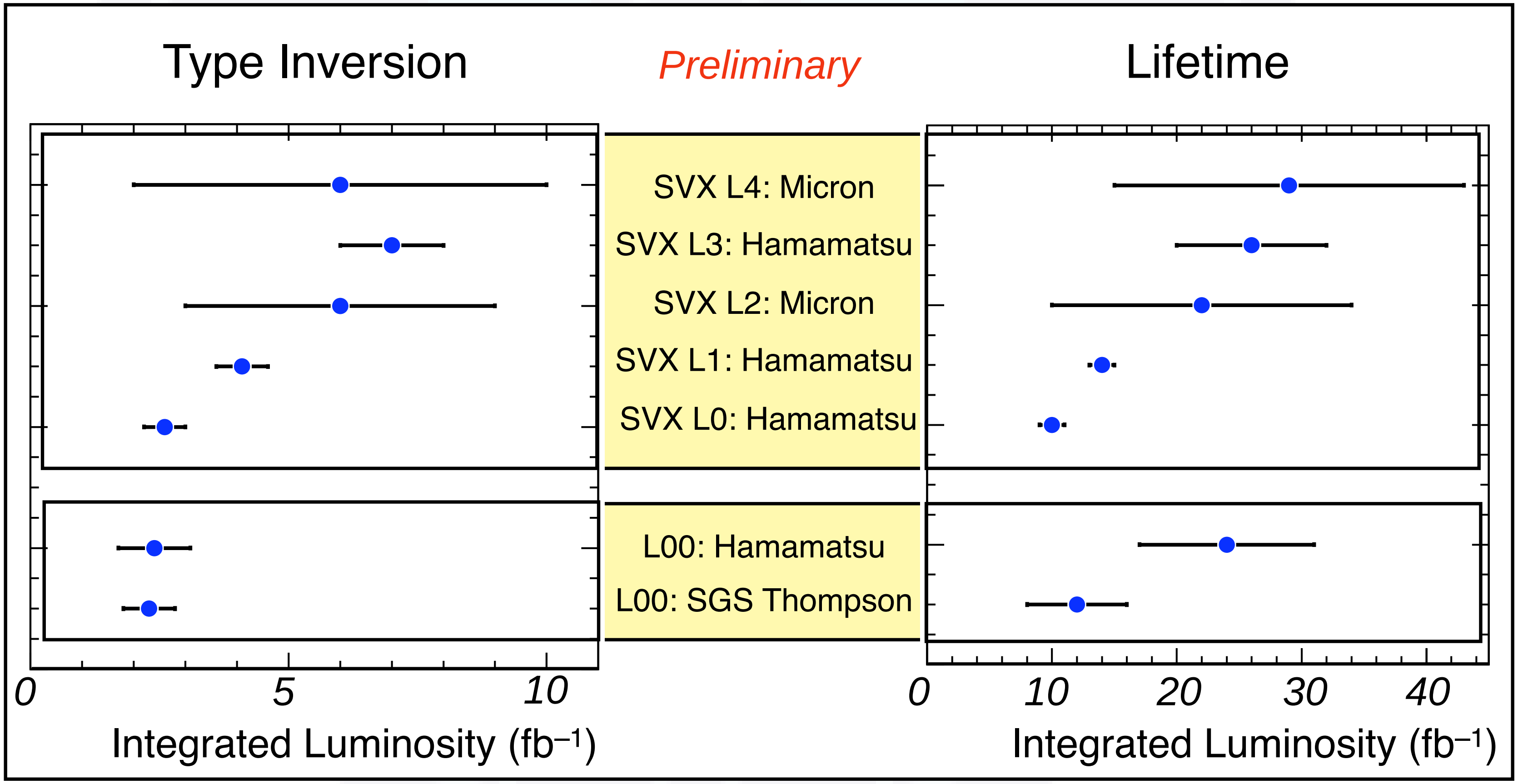
- Straight-line extrapolation of depletion voltage:



→ Data consistent with lifetime prediction

Type Inversion & Lifetime

- Results presented as mean and RMS of fits for individual ladders
- Lifetime: assume same slope $|dV_{dep}/d\int L dt|$ after inversion



Summary and Conclusions

- CDF silicon detectors are operated in harsh radiation environment: detailed evaluation of detector longevity
- Beam-related incidents influence silicon operation:
  - Abort kicker prefires: destroyed readout chips
  - Single-event upsets: power supply problems
- Lifetime limited by depletion voltage and noise
- Extrapolations of point of type inversion and lifetime: silicon detectors is expected to live through Tevatron Run II

Further CDF talks at this workshop:
Sebastian Grinstein: *CDF Vertex Detector* (9 November, 16:00)
Roberto Carosi: *Vertexing at CDF* (9 November, 16:30)