Aging Effects and Operational Experience with the CDF Run II Silicon Detector

U. Husemann on behalf of the CDF Collaboration

***Abstract*—The silicon detector system of the CDF-II experiment at the Tevatron proton-antiproton collider at Fermi National Accelerator Laboratory has been operated successfully since the start of Tevatron Run II in 2001. In this article we summarize the experience gained with the silicon detector system, focusing on automation and aging effects of detector components during the years 2006–2008. In addition, we present the most recent updates on studies of single event upsets and radiation damage to the silicon sensors.**

***Index Terms*—High-energy physics instrumentation, silicon strip detectors, radiation damage**

I. Introduction

THE CDF-II detector at the Tevatron collider at Fermi National Accelerator Laboratory (FNAL) is a multi-purpose particle physics detector built to study proton-antiproton collisions at a center of mass energy of 1.96 TeV. The CDF tracking system is instrumental to the physics program, providing excellent momentum and impact parameter resolutions for charged particle tracks. It is comprised of a silicon detector system with 7–8 layers of silicon micro-strip detectors and a large drift chamber. A description of the CDF-II detector can be found elsewhere [1].

The silicon detector system consists of three sub-detectors; Table I summarizes some of their basic parameters. Layer 00 (L00) [2] is installed directly on the beam pipe. The sensors are single-sided p-in-n sensors that follow the same design rules as the silicon sensors used in the CMS experiment [3] at the LHC. Some of the narrow sensors are made of oxygenated silicon. The SVX-II detector [4] is the core detector for silicon tracking and for a trigger on tracks with large impact parameter with respect to the interaction point [5]. SVX-II features five layers of double-sided silicon sensors. The Intermediate Silicon Layers (ISL) [6] are comprised of a single layer of double-sided sensors in the central detector region ($|\eta| < 1.0$) and two layers in the forward regions ($1.0 < |\eta| < 2.0$).[1] In SVX-II and ISL, two types of double-sided sensors are used, with micro-strip orientations in $r\phi$ direction on one side and perpendicular or at an angle of $1.2°$ with respect to the beam axis on the other side, as shown in Table I.

The CDF-II silicon detector system was commissioned successfully at the beginning of Tevatron Run II in 2001–2002 and will be operated until the end of Run II in 2009, with a possible extension to 2010. Having operated the system for many years, the CDF collaboration has gained valuable experience with silicon detectors at a hadron collider. At the same time, detecting and mitigating aging effects of both the silicon sensors and the detector infrastructure has become increasingly important.

TABLE I
Overview of Layer 00 and SVX-II parameters.

Name	Radius (cm)	Orient.	Manufacturer
L00 (narrow)	1.35	$r\phi$	SGS Thomson, Micron
L00 (wide)	1.62	$r\phi$	Hamamatsu
SVX L0	2.54	$r\phi, z$	Hamamatsu
SVX L1	4.12	$r\phi, z$	Hamamatsu
SVX L2	6.52	$r\phi, 1.2°$	Micron
SVX L3	8.22	$r\phi, z$	Hamamatsu
SVX L4	10.10	$r\phi, 1.2°$	Micron
ISL L6 Central	22.0	$r\phi, 1.2°$	Hamamatsu
ISL L6 F/B	20.0	$r\phi, 1.2°$	Hamamatsu
ISL L7 F/B	28.0	$r\phi, 1.2°$	Micron

II. Operational Experience

A. Strategies of Detector Operation

Silicon detector operation in CDF Run II can be divided into two periods. After the long commissioning period of 1.5 years, the primary goal was to maximize the number of detector channels returning good data. This goal was achieved by two measures, by vigilant monitoring of the detector with a comprehensive set of monitoring tools on all levels and by frequent access to the CDF collision hall to investigate and resolve detector hardware problems. This, person power intensive yet very successful, strategy allowed the silicon detector operation group to achieve and preserve peak detector performance over many years, see e.g. [7].

The second period started around 2006, when the vast majority of failure modes was known and detailed procedures for mitigation and recovery were in place. During this time, the operation group started to automate the most important of these procedures. This allowed to recover from failures faster and with less intervention by the shift crew and had the additional advantage of reducing the person power required to operate the detector.

B. Automatic Recovery of Power Supply Failures

The power for the silicon detectors is supplied by 113 custom power supply modules installed in 16 CAEN SY527 mainframes [8] in the CDF collision hall. The mainframes communicate with the slow control system via V288 CAENET

Corresponding author: U. Husemann, Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D–15738 Zeuthen, Germany. E-Mail: ulrich.husemann@desy.de

[1]In the CDF geometry, r is the radial distance from the beam axis, θ is the polar angle with respect to the proton beam (positive z direction), and ϕ is the azimuthal angle. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

controllers [9]. With a frequency of about one per day, communication with one of the mainframes is lost. We have developed a two-step procedure to recover from this failure mode automatically.

The first step is to detect the communication loss and reset the mainframe. This is achieved by evaluating the mainframe status in 7 second cycles and issuing a $5\,\mathrm{V}$ reset signal to the mainframe once communication loss is reported for two consecutive cycles. The reset is implemented with a National Instruments PCI-6516 digital output card [10] installed in one of the slow control PCs. A custom reset panel provides power to the reset lines and allows for manual instead of automated resets. A manual reset can also be issued remotely via the slow control system.

With the reset, all power supply modules in the affected mainframe are switched off. This condition will halt data-taking until all detector channels receive their regular voltage again. We developed the Silicon Auto-Recovery (SAR) tool to automate the recovery of power supply channels that are without power. The recovery procedure involves synchronized actions in both the slow control and the data acquisition (DAQ) system. SAR detects detector channels without power during data-taking and requests that the slow control turn these channels back on. Once the low voltage power to the detector channels is restored, the readout chips [11] need to be initialized by taking them through the appropriate transitions of the DAQ state machine. This is done only for those parts of the DAQ that are affected by the failure. At this point the failure is recovered and data-taking can continue.

Automating the power supply mainframe reset and the recovery of all channels served by the mainframe has reduced the average data-taking down-time due to lost communication with a mainframe from 5–10 minutes for a fully manual intervention by the shift crew to about 1.5–2 minutes and therefore increased the uptime of the silicon detectors significantly.

III. Infrastructure Aging

The long-term operation of a complex detector system like the CDF Run II silicon detectors may lead to temporary performance loss due to unexpected aging effects. In the following we will describe two effects that were discovered and successfully mitigated in 2007.

A. Power Supplies

In early 2007, the slow control monitoring showed indications that some power supplies lost the ability to provide nominal low voltage to the readout chips and optical transmitters, in a slow process over a few 100 days of operation. This "drooping voltage" problem was tracked down to the aging of one type of $10\,\mu\mathrm{F}$ regulating capacitor on the power supply modules that steps down the voltage from $72\,\mathrm{V}$ to $-12\,\mathrm{V}$. As the same type of capacitor is used for other circuits on the power supplies, the observed aging effect must be electrical. The problem was resolved by replacing the capacitors at the FNAL Electronics System Engineering department; however, replacing 36 capacitors each on a total of more than 75 power supplies was a major logistical effort. The repair work has been conducted before, during, and after a 10 week Tevatron shutdown in summer 2007; all affected power supplies have been fully recovered.

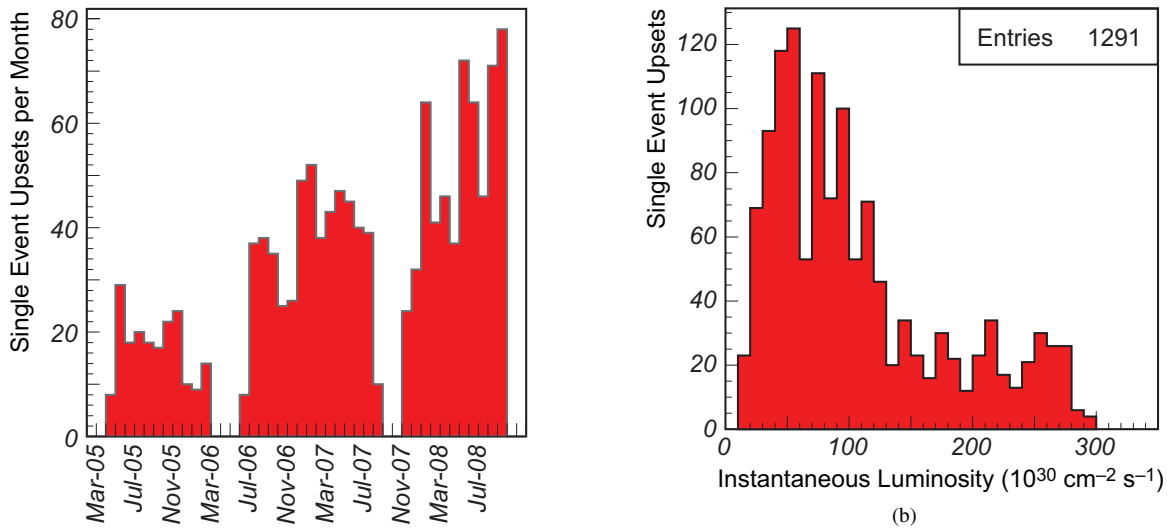
B. Cooling System

The CDF silicon detectors are cooled by two independent mono-phase liquid cooling systems that run sub-atmospheric. The L00 and SVX-II detectors are cooled with a mixture of 70% water and 30% ethylene glycol at $-10^\circ\mathrm{C}$. ISL and all electronics run at $+6^\circ\mathrm{C}$. It was realized in 2005 that the cold spots of the ISL/electronics cooling system may reach temperatures below $0^\circ\mathrm{C}$ under special conditions. Therefore the coolant was changed from pure water to a 90/10 mixture of water and ethylene glycol.

In early 2007 it was realized that the coolant had turned acidic, approaching a pH of around 2, a process that had likely started after a Tevatron shutdown in spring 2006. An ion chromatography analysis showed that the ethylene glycol had broken down to carbolyxic acids, mainly formic acid.[2] The pH of the coolant was successfully reduced by two measures, draining and flushing the cooling system, and connecting the system to large ion exchangers. We compensated for the loss in passive freeze protection through the glycol by implementing an active protection via the interlock system. However, leaks had already developed in the aluminum piping (made out of "6061 Al" alloy), so that from May 2007 parts of the ISL and the entire L00 could not be operated. The leaks were restricted to the heat-affected zones around the aluminum welds that connect the supply and return pipes to rings of cooling pipes.

The repair of the leaks was complicated by limited accessibility and the danger of increasing the adverse effects of radiation damage to the silicon sensors. The leaks were located about $1\,\mathrm{m}$ inside the last accessible point of the system at the end-plates of CDF's large drift chamber. Therefore the repair work had to be performed from the inside of the cooling pipes, breaking the seal that protects the silicon detector volume from the collision hall environment. At the time of the incident, the inner silicon layers had already undergone type inversion (see Sect. IV-B). To mitigate the effects of radiation damage on the ability to fully deplete the sensors, the sensors had to be kept as cold as possible. A dry air tent was designed and constructed to keep the dew point in the work space and the silicon detector volume below $-10^\circ\mathrm{C}$ and thus to avoid condensation on the silicon detectors during the repair.

The repair was performed during a 10 week shutdown in summer 2007, using medical equipment such as borescopes and catheters. The entire heat-affected zones around the aluminum were coated with DP-190 epoxy, which was applied through a $0.75\,\mathrm{mm}$ brass tube and cured with dry nitrogen for at least 24 hours. With the repaired cooling system, and with improved instrumentation, the detector cooling system is running stable since October 2007 and all of ISL and L00 are operational again.



(a) (b)

Fig. 1. (a) Number of micro-sequencer memory corruptions as a function of time. (b) Number of micro-sequencer memory corruptions as a function of instantaneous luminosity.

IV. Effects of Radiation

A. Single Event Upsets

The Fiber Interface Boards (FIB), a part of the silicon detector DAQ system, are located in the four corners of the CDF collision hall and are therefore exposed to radiation during $p\bar{p}$ collisions. The command sequences for the readout chips are stored in an on-board EEPROM and copied to the micro-sequencer memory when the FIB is powered up. The memory content is compared with the EEPROM every time the DAQ requests initialization of the readout chips. We record the number of memory corruption events due to single event upsets (SEU) as a function of time and instantaneous luminosity. As shown in Fig. 1 (a) the SEU rate increases as a function of time. At the same time there are no indications for a dependence of the SEU rate on instantaneous luminosity, as can be seen from Fig. 1 (b), where the number of SEUs roughly follows the Tevatron instantaneous luminosity profile. These findings suggest that the SEU rate depends on the total radiation dose rather than the dose rate.

B. Depletion Voltages

As of November 2008, the Tevatron has delivered a total integrated luminosity of more than $5\,\mathrm{fb}^{-1}$ per experiment, with an expected $6{-}7\,\mathrm{fb}^{-1}$ by the end of Tevatron Run II in 2009. The option of running the Tevatron in 2010 is currently under discussion. The silicon detectors had originally been designed to be radiation hard up to $2{-}3\,\mathrm{fb}^{-1}$, but in 2004 we identified and implemented a set of operational measures to preserve excellent performance for integrated luminosities of at least $7{-}8\,\mathrm{fb}^{-1}$.

Detailed measurements of the radiation field were performed with more than 1000 thermal luminescent dosimeters distributed over the detector volume [12]. Extrapolating from these measurements with an inverse power law in r, L00 (SVX L0, SVX L1) has been irradiated with a dose of approximately $50\,\mathrm{kGy}$ ($20\,\mathrm{kGy}$, $10\,\mathrm{kGy}$).

The efficiency of a silicon sensor depends on the amount of charge collected when a charged particle traverses the sensitive volume of the sensor. The signal is maximal when the sensor is fully depleted by applying an appropriate (reverse) bias voltage. Under irradiation and annealing, the effective number of charge carriers in a silicon sensors changes. As a consequence, the silicon sensor bulk undergoes "type inversion," i.e. the sensor material changes from net n type to p type. The bias voltage required to fully deplete the sensor, V_{dep}, decreases to the point of type inversion and then increases again, eventually surpassing the maximum voltage the power supply can provide or the breakdown voltage of the sensor. In L00, the limit of $500\,\mathrm{V}$ is given by the power supply, in SVX by micro-discharges in the sensors (L0, L1, L3: $170\,\mathrm{V}$; L2, L4: $70\,\mathrm{V}$).

We have monitored V_{dep} as a function of the integrated luminosity with signal bias scans on a regular basis (currently: monthly) [13]. In a signal bias scan, the bias voltage is increased in steps from $0\mathrm{V}$ to a maximum voltage. The average charge at a given voltage is extracted from the most probable value of the path-length corrected ADC spectrum of hits on good tracks. We then define V_{dep} as the voltage for which 95% of the maximum charge is reached, see Fig. 2 for an illustration. To extrapolate to the full integrated luminosity expected at Tevatron Run II we plot V_{dep} as a function of integrated luminosity and perform a straight line fit to all data points after type inversion. The results are shown in Fig. 3 for L00 and in Fig. 4 for L0 and L1. They show that these inner layers of the CDF silicon system are all beyond type inversion. It is interesting to note that the oxygenated L00 sensors have type-inverted at a higher integrated luminosity than the standard sensors at the same radius. The extrapolations suggest that L00, L0, and L1 will outlast Tevatron Run II.

[2]The SVX-II/L00 coolant never showed a pH below 4.

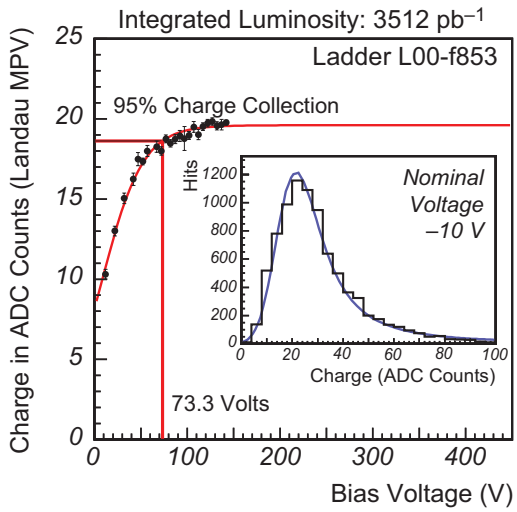


Fig. 2. Determination of the depletion voltage V_{dep} for a single L00 module. The most probably charge of the measured ADC spectrum of hits on good tracks is plotted against the applied bias voltage, and V_{dep} is determined as the bias voltage for which 95% of the plateau is reached.

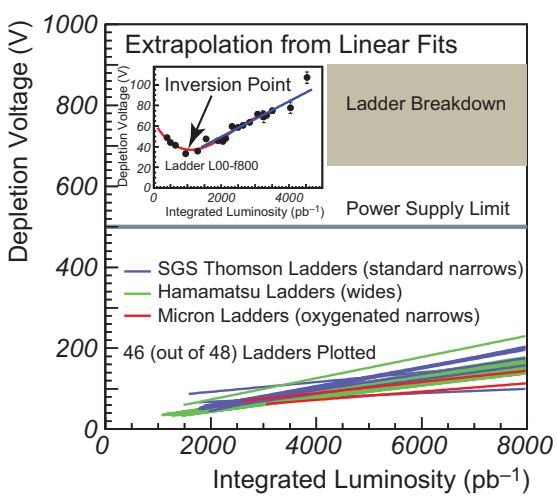


Fig. 3. Extrapolation of depletion voltages for L00. The inset shows the depletion voltage as a function of integrated luminosity for a single L00 module. The data is fitted with a third order polynomial to determine the point of type inversion (red curve) and with a straight line after type inversion to extrapolate to the full Tevatron Run II luminosity (blue curve). The main plot summarizes all extrapolations for L00.

V. Conclusion

In this article we have summarized operational experience with the CDF silicon detectors in Tevatron Run II. We have described how the silicon operation group has solved recent infrastructure aging problems such as drooping low voltages in the power supply modules and leaks in the ISL cooling system. We have also presented the most recent results of SEU studies on the FIBs and signal bias scans that assess the radiation damage to the silicon sensors. The scans indicate that the sensors both in L00 and in SVX L0 and L1 will outlast Run II.

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References

[1] D. E. Acosta *et al.*, "Measurement of the cross section for $t\bar{t}$ production in $p\bar{p}$ collisions using the kinematics of lepton + jets events," *Phys. Rev.*, vol. D72, p. 052003, 2005.
[2] C. S. Hill *et al.*, "Initial experience with the CDF Layer 00 silicon detector," *Nucl. Instrum. Meth.*, vol. A511, pp. 118–120, 2003.
[3] R. Adolphi *et al.*, "The CMS experiment at the CERN LHC," *JINST*, vol. 3, p. S08004, 2008.
[4] A. Sill *et al.*, "CDF Run II silicon tracking projects," *Nucl. Instrum. Meth.*, vol. A447, pp. 1–8, 2000.
[5] W. Ashmanskas *et al.*, "The CDF silicon vertex trigger," *Nucl. Instrum. Meth.*, vol. A518, pp. 532–536, 2004.
[6] A. Affolder *et al.*, "Intermediate silicon layers detector for the CDF experiment," *Nucl. Instrum. Meth.*, vol. A453, pp. 84–88, 2000.
[7] B. Brau, "Operational experience with the CDF Run 2 silicon tracker," *Nucl. Instrum. Meth.*, vol. A541, pp. 73–77, 2005.
[8] *MOD. SY 527 Universal Multichannel Power Supply System*, CAEN S.p.A., 1995.
[9] *MOD. V288 H. S. Caenet Vme Controller*, CAEN S.p.A., 1992.
[10] *NI PCI-6516 (32 Source Outputs) Low-Cost 37-Pin Industrial Digital Source Output*, National Instruments Corp., 2006.
[11] M. Garcia-Sciveres *et al.*, "The SVX3D integrated circuit for dead-timeless silicon strip readout," *Nucl. Instrum. Meth.*, vol. A435, pp. 58–64, 1999.
[12] R. J. Tesarek *et al.*, "A measurement of the radiation environment in the CDF tracking volume," *Nucl. Instrum. Meth.*, vol. A514, pp. 188–193, 2003.
[13] A. Boveia, "Status and performance of the CDF Run II silicon detector," *PoS*, vol. HEP2005, p. 377, 2006.

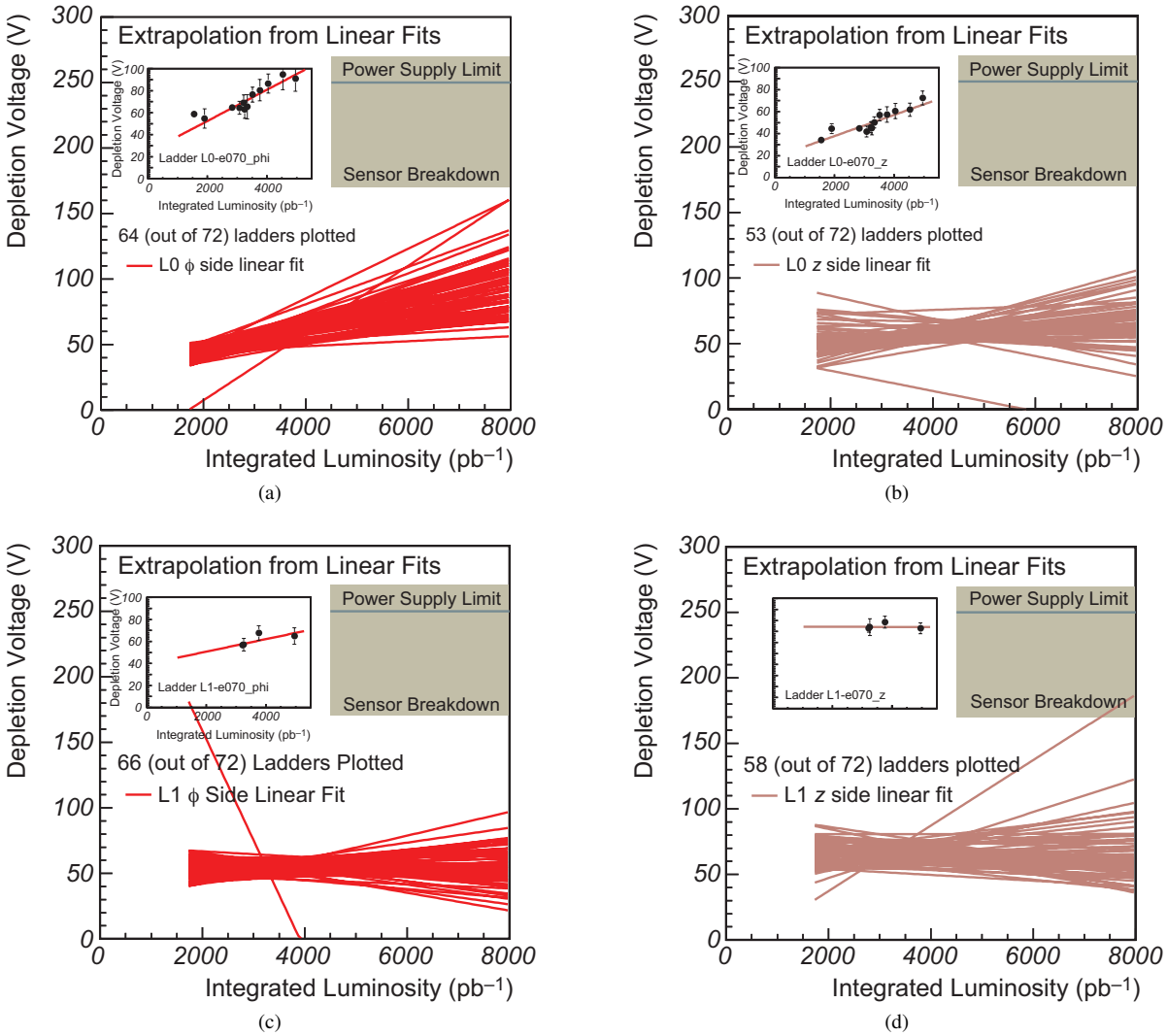

Fig. 4. Extrapolations of depletion voltages for (a) the $r\phi$ side of L0, (b) the z side of L0, (c) the $r\phi$ side of L1, (d) the z side of L1. The insets show the depletion voltage as a function of integrated luminosity for a single module after type inversion. The data is fitted with a straight line to extrapolate to the full Tevatron Run II luminosity (red curve). The main plots summarize all extrapolations.