Fermilab

FERMILAB-CONF-09-041-E

Operational Experience with the CDF Run II Silicon Detector

Ricardo Eusebi *
on behalf of the CDF Run II silicon group
Fermi National Accelerator Laboratory
Batavia, 60510, Illinois, USA.

Abstract

The CDF Run II silicon detector is currently the largest operating silicon detector in High Energy Physics. Its 750,000 channels, spread over 6 m^2 of p-on-n silicon sensors, and allow precision tracking of charged particles and vertexing at the 50 μm level. The CDF Run II silicon detector is fundamental for all branches of the CDF physics program. It played a critical role in the discovery of B_s mixing and is used extensively for the current Higgs boson searches at the forefront of the energy frontier. Over the last 6 years, the detector efficiency has remained stable above 95 % after the Run II commissioning period. While originally designed to withstanding up to 3 fb^{-1} of data, the CDF II silicon detector will have to last to the end of Run II where 5–8 fb^{-1} of data is expected to be delivered. This letter presents the observed effects of infrastructure aging and the solutions implemented to prevent them, followed by the assessment on radiation damage and expected performance to the end of the Tevatron Run II program. The radiation aging of such a large scale system is particular relevant for future silicon detectors in hadronic colliders as LHC.

Key words: Silicon, detector, vertex, aging, radiation damage
PACS: 29.40.Gx, 29.40.Wk, 07.00.00, 95.55.Vj,

1. The CDF Silicon Detector in Run II

Located at the Fermi National Accelerator Laboratory the Tevatron collider is the highest-energy particle collider in the world. The Tevatron is a circular synchrotron accelerator with a radius of 1 Km that brings protons and anti-protons into collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The collisions happen in two points on the Tevatron ring where two multi-purpose particle detectors are located surrounding their respective interaction points. One of these detectors is the Collider Detector at Fermilab, or CDF.

The silicon vertex detector is one of the core components of the CDF detector. It is the sub-detector closest to the interaction point allowing for precision tracking and vertexing. It is used in the CDF Silicon Vertex Trigger [1], the first hardware displaced vertex trigger implemented at a hadron collider detector. The CDF silicon vertex detector is one of the largest operating silicon detectors in particle physics. It comprises eight concentric layers of silicon micro-strip sensors with a total of 722,432 channels read out by 5,456 SVX3D chips [2]. The total surface area covered by the silicon sensors amounts to 6 m^2. The detector is distinguished by its physical characteristics into three subdetectors: Layer 00 (L00), SVX-II, and the Intermediate Silicon Layers (ISL).

* Corresponding author. Tel: +1-630-840-4326
Email address: eusebi@fnal.gov (Ricardo Eusebi).

1.1. *L00*

The L00 detector [3] is mounted directly on the Tevatron beam pipe. L00 uses radiation-hard, single-sided sensors, from Hamamatsu at a radius 1.62 cm, and from SGS Thomson and Micron at a radius 1.35 cm. The sensors were fabricated with design rules similar to those in use at the Compact Muon Solenoid (CMS) silicon tracker. Its low amount of material, of only $\sim 0.01 X_0$, and proximity to the interaction point allow for precision position measurements before charged particles undergo any significant scattering in the detector material.

The strip pitch is of 25 μm but only every other strip is read out. The breakdown voltage of the L00 sensors starts at 650 V, but the maximum applied bias voltage is limited by the power supplies to 500 V.

1.2. *SVX-II*

SVX-II [4] is the core of the silicon detector and is the only component used in the hardware trigger for events with displaced vertices [1]. The SVX-II detector has 5 layers of double-sided sensors located at radii from 2.5 cm to 10.6 cm. Three layers are made of Hamamatsu silicon with the n strips perpendicular to the p strips. The remaining two layers are Micron sensors with a stereo angle of 1.2^o between the p and n strips. The strip pitch varies between 60 μm to 140 μm, depending on the layer radius. The maximum bias voltages that can be applied to Hamamatsu and Micron sensors are 170 V and 70 V respectively, limited by the breakdown voltage of the integrated coupling capacitors and other sensor-fabrication characteristics.

1.3. *ISL*

ISL [5] is the outer most component of the CDF silicon detector. It provides an extended forward coverage and links tracks between the CDF wire chamber surrounding the silicon detectors and SVX-II. The ISL detector has one central layer at radius of 22 cm and two forward layers at radii of 20 cm and 28 cm. It is made of double-sided sensors with strips at a stereo angle of 1.2^o, and a strip pitch of 112 μm. The breakdown voltage of the sensors is 100 V limited by the breakdown voltage of the coupling capacitors. The power supplies can provide voltages up to 250 V.

2. Operational Experience During Commissioning

During the commissioning phase of the CDF Run II Silicon detector there were a number of operational challenges. One of the first challenges was the discovery and repair of blocked cooling lines in the ISL detector in which glue, deposited during the assembly of the detector, fully blocked the cooling lines. The repair was complicated by the direct inaccessibility to the inside of the silicon detector volume. The solution was to blow the glue deposits using a powerful laser connected to a fiber optic that was inserted through the cooling lines to the point of blockage. Details of this procedure can be found at [9].

Another challenging problem was related with wire-bond resonances. It was found that during special data-taking conditions a few SVX-II chips lost their powering of their "z" side. This was then traced to the fact that the wire-bond carrying the power was oriented perpendicular to the magnetic field permeating the silicon detector. As a consequence, and depending on the synchronicity of the readout, the wire-bond resonates and eventually breaks. The implemented solution was to stop data-taking if the SVX-II readout frequency becomes synchronic. See[10] for details.

Among the major operational challenges was that of beam incidents. The condition of the beam and its transportation around the Tevatron ring can have a major impact on the life of the silicon sensor. In one particular incident the beam lost control in such a way that magnets on 16 of the so-called "houses" of the Tevatron loose their superconductivity. This beam incident resulted in the lost of a few readout chips of the CDF silicon detector. Many preventive steps were taken, including the installation of a special collimator close to CDF, the installation of a new beam monitoring and abort system [11], and the requirement of special procedures to guarantee the safe operation of some key elements of the Tevatron.

3. Infrastructure Aging

The infrastructure supporting the operation of the silicon detector is a complex system, involving fiber-optics, power supplies, cooling systems and data acquisition electronic. Aging occurring to these systems can reduce the operational efficiency.

3.1. *Cooling System*

In May 2007 the pipe cooling the optical transmitters reading out one half of ISL/L00 suffered a leak, making impossible the operation of that part of the system. It is suspected that the leak was caused by the acidification of the coolant during the 2006 shutdown, which was only identified in March 2007 when the pH had reached 2 and conductivity rose to 3300 μSi/cm. The ISL coolant, composed of 10% glycol on water, was neutralized by draining and deionizing it with a resin bed bringing the pH to 5 and the conductivity to 5 μSi/cm.

Ion chromatography analysis shows that the main source of acid was the oxidation of glycol into carboxylic acids, mainly formic acid. The repair was performed from the inside of the pipe using medical equipment such as boroscopes and catheters, and small custom-made brass wires to deposit DP190 epoxy in the corroded areas. To fix the problem from inside the pipes was the only solution since the access to the outside of the pipe, well inside the CDF detector is virtually impossible. After a few weeks of repair work the full system could be successfully operated and readout. Is it interesting to note that the SVX cooling system, running 30% glycol in water, and at a temperature 10 C^o lower, never had this problem and has always stayed above pH 4.

3.2. *Power Supplies*

The power to the chips and the optical transmitters for the silicon detector are supplied by CAEN modules. A total of 114 CAEN power supply modules are used to power the detector. The modules are located in 16 CAEN SY527 crates inside the CDF Collision Hall, and are therefore exposed to the radiation field.

During last year a failure mode of these modules was detected. For some of the channels and power supplies modules, the voltage delivered started to drop slowly over time becoming erratic after some weeks. The problem was tracked down to aging of one kind of 10 μF capacitor in the power supply boards. Each power supply module draws 310 V from the crate backplane which is stepped down to 72 V in a central supply for all the layers of the module.

Secondly, in each layer board these are further stepped down to 5 V and $\pm$12 V. These voltages are used to power the analogue and digital parts of the SVX3D chips as well as the optical transmitters. For each layer, 3 capacitors were found to age for each of the chip voltages, and 6 for the optical transmitter channels. This made a total of 36 bad capacitors for each PS module. Although all the capacitors are of the same type several more are present in various non-critical circuits of the PS modules.

A total of 60 power supply modules were extracted, repaired on site, checked, and reinstalled in the system since the 2007 shutdown. All the modules with this failure mode have been repaired.

4. Radiation Damage

To this date, the total integrated luminosity delivered by Tevatron is of 3.8 fb^{-1} per experiment. This amount already exceeds the design specification for the silicon detector to be radiation hard up to 3 fb^{-1}. The accelerator will run through 2009 with the expectation to deliver from 5.8 fb^{-1} to 6.8 fb^{-1}. The option to run in 2010 is currently under discussion having been recently endorsed by the laboratory and the two experiments.

The CDF silicon detector is located in an intense radiation field. Measurement of the ionizing radiation dose at various points of the detector was done early in Run II [6] by means of more than 1000 thermal luminescent dosimeters spread over the entire detector volume. An extrapolation of the measured dose using an inverse power law in r gives an estimate for the ionizing radiation dose of 300 ± 15 kRad/fb^{-1} at a radius of 3 cm with a 20 % variation over z.

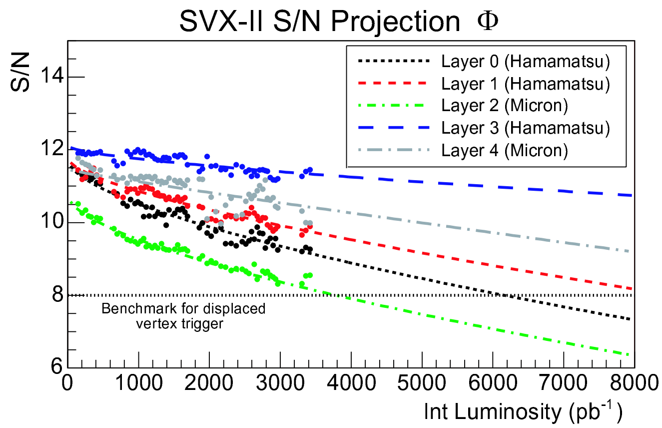

Fig. 1. Measured signal to noise ratio for each of the 5 SVX layers as a function of the luminosity. Good trigger efficiencies are expected for overall signal to noise ratios above 8. The b-tagging efficiency is expected to be good for values above 3.

This means that L00 and the inner layer of SVX-II have already received doses of $\sim$ 3.8 MRad and $\sim$ 1.5 MRad, respectively during Run II. The flux to luminosity factor has been measured using the increase of leakage current of the sensors themselves.

The performance of the readout electronics located inside the detector is not expected to be seriously compromised by the integrated radiation dose. The SVX3D chip [2] noise is predicted to increase by 17 % after 8 fb^{-1} while the light output from the Dense Optical Interface Module is expected to degrade by 10 %[7].

Radiation damage affects the operation of the silicon detector in two ways: via the degradation of signal and increase of noise, and via the increase of the depletion voltage.

5. Degradation of Signal and Increase of Noise

Defects in silicon crystals due to radiation damage lead to an increase of the sensor leakage current and, as a consequence, to an increase of sensor shot noise. In addition, signal quality degrades as crystal defects cause degradation of charge collection efficiency via trapping and changes in the time response of the sensor.

The performance of the silicon sensors can be quantified by mean of the signal to noise charge ratio. Performance studies indicate that a good trigger efficiency is achievable with overall signal to noise ratios above 8, while for b-tagging efficiency the ratio must be over 3.

The signal charge is the amount of charge left by a minimum ionizing particle in its pass through the sensor, and it is obtained by using a clean sample of tracks from data collected with J/Ψ triggers in normal physics data. The tracks are associated with a strip on the sensors and the charge deposited in the strip is considered from real-particle signal. The signal charge distribution of signal forms a Landau distribution.

The noise is estimated using special calibration runs with beam in which data is collected at random, and the charge distribution in the collected events is expected to be coming from noise. Figure 1 shows the measured signal to noise ratio for the 5 SVX layers as a function of the luminosity along with extrapolations [8] that suggest appropriate values up to 8 fb^{-1}.

6. Increase of Depletion Voltage

Damage to the bulk causes the number of effective charge carriers to change, gradually decreasing the voltage required to deplete the sensor until type inversion, after which the depletion voltage increases. To continue having fully depleted sensors the voltage needs to be raised to keep up with the radiation damage until one of either two things happens: the voltage get too close to the breakdown voltage of the sensor, or the power supply maximum voltage is reached. These section shows that the sensors will be fully depleted until the end of Run II.

For a given luminosity the depletion voltage is measured with a special run in which the sensors are biased in incremental steps from 0 V to a maximum voltage that depends on the type of sensor. From this data the most probable charge value is obtained as a function of bias voltage as shown in Figure 2 for a L00 sensor. The plot is fit to a sigmoid function, where the charge of the plateau is identified the voltage corresponding to 95 % the charge of the plateau is defined as the depletion voltage.

The evolution with luminosity of the depletion voltage for one L00 module is shown in the inset of Figure 3. The lower depletion voltage at a luminosity of about 1.1 fb^{-1} indicates the moment in which the module passed inversion. The solid (red) curve is a polynomial of 3^{rd} order fitted to the data points used to estimate the moment of inversion. The dashed (blue) curve is a linear fit to predict the evolution of the depletion voltage as a function of luminosity. The main body of Figure 3 shows the predicted voltage as a function of luminosity, the breakdown voltage of the sensors, the maximum voltage the PS could provide, and the linear extrapolation for all the sensors composing the L00 detector. This plot shows that the increase in depletion voltage from the data will not reach the breakdown voltage nor the maximum power supply limit of 500 V and will survive throughout the life of Run II.

7. Summary

The operation of the CDF Run II silicon detector has overcome important challenges, from clogged cooling lines and acidic coolant to wire-bond breakups and aging of the power supplies. The two inner layers of the CDF silicon detector have passed type inversion but predictions indicate that the sensors will continue to perform well through the end of Run II. Today the CDF Run II silicon is running with 92 % of all sensors and with a data-taking efficiency greater than 97 %.

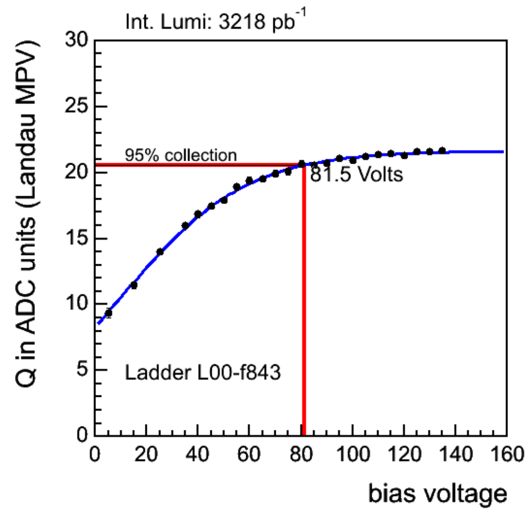

Fig. 2. Most probable value of the charge distribution from hits collected with one L00 module as a function of applied bias voltage. The vertical (red) line indicates the measured depletion voltage.

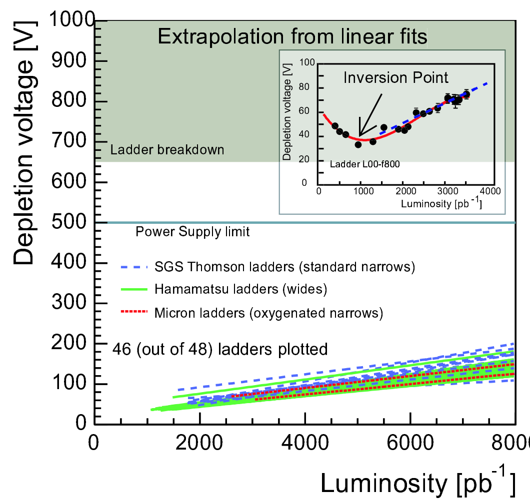

Fig. 3. L00 depletion voltage vs Luminosity. The inset shows the measured depletion voltage vs. luminosity for one L00 module. The main plot displays the linear extrapolations up to 8 fb^{-1} from fits to data after inversion for all L00 modules.

References

[1] W. Ashmanskas *et. al.*, Nucl. Instrum. Meth. A **518**, 532 (2004).
[2] M. Garcia-Sciveres *et. al.*, Nucl. Instrum. Meth. A **435**, 58 (1999).
[3] C.S. Hill *et. al.*, Nucl. Instrum. Meth. A **511**, 118 (2003).
[4] A. Sill *et. al.*, Nucl. Instrum. Meth. A **447**, 1 (2000).
[5] A. Affolder *et. al.*, Nucl. Instrum. Meth. A **453**, 84 (2000).
[6] R.J. Tesarek *et. al.*, Nucl. Instrum. Meth. A **514**, 188 (2003).
[7] R.S. Lu *et. al.*, Nucl. Instrum. Meth. A **552**, 219 (2005).
[8] A. Mitra, Nucl. Instrum. Meth. A **573**, 273 (2007).
[9] B. Brau, Nucl. Instrum. Meth. A **541**, 73 (2005).
[10] G. Bolla *et. al.*, Nucl. Instrum. Meth. A **518**, 277 (2004)
[11] P. Dong *et. al.*, IEEE TNS Proceedings of the 15^{th} conference on real time, Part I, 328 (2007).