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Radiation hardness experience with the CDF/DØ Silicon vertex detectors

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Abstract

The two Tevatron experiments, CDF and DØ, have been taking data with their silicon detectors since the beginning of 2002. Up to September 2006, the Tevatron has delivered an integrated luminosity of almost 2 fb^{-1}. Both experiments continuously monitor their detectors for silicon sensor damage due to radiation. These results allow both experiments to make predictions of the lifetime for their silicon detectors.

Key words: CDF, DØ , Silicon Detector, Radiation Damage
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1. Introduction

The Tevatron is the world's most powerful $p\bar{p}$ collider with a circumference of 6.28 km and a centre-of-mass energy of 1.96 TeV. The Run-II of the Tevatron has been ongoing since 2001 and has achieved a peak luminosity of $231{\cdot}10^{30}\text{cm}^{-2}/\text{s}$. Altogether both experiments have integrated 1.8 fb^{-1} each for Run-II compared to Run-I's 150 pb^{-1}. The Tevatron is expected to deliver between 5 and 8 fb^{-1} for both experiments till the end of 2009.

Both experiments consider the aging of the sensors due to radiation damage as the limiting factor for the detector lifetime. They define two criteria that are expected to limit the lifetime of the detector. The first one is the inability to deplete the sensors fully and the second is an insufficient signal to noise ratio even if the sensors can be still fully depleted.

2. The CDF Silicon detector

The CDF Silicon detector is the largest operating detector of its kind at a collider experiment. It consists out of three separate subdetectors: Silicon Vertex II (SVX-II), Intermediate Silicon Layers (ISL) and Layer 00 (L00) (see Fig. 1). The SVX-II [2] is the core of the CDF Silicon detector [1]. It is designed both as a high resolution (<30 μm) vertex detector and to serve as input to a displaced vertex trigger. It consists of five layers of double-sided silicon modules. The layer 0, 1 and 3 modules have $r\phi$ and rZ sides and were manufactured by Hamamatsu, while layers 2 and 4 have $r\phi$ and

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[2] SVX-II layers are numbered from 0.

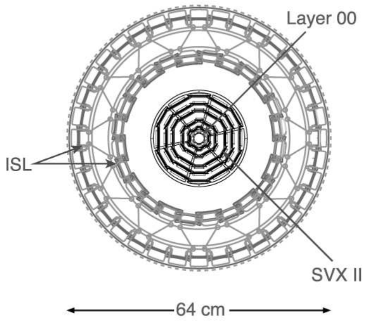

Fig. 1. Endview of the CDF silicon detector with ISL, SVX-II and L00

1.2 degree small angle stereo sides and were made by Micron. The detector consists of six bulkheads, each with twelve wedges, consisting out of five layers. Altogether there are 360 modules that are read out in parallel. The electronics are mounted on the sensors and the data is read out using a custom ASIC, the SVX3D chip. The SVX3D consists of an analog pipeline front-end and a digital back-end. The chip provides 128 channels and is capable of deadtime-less operation.

The ISL (Intermediate Silicon Layers) [2] is located between the wire tracking chamber (COT) and the SVX-II. The ISL consists of one central barrel with one layer and two forward barrels consisting of two layers. Sensors were manufactured by Micron (inner layer) and Hamamatsu (outer layer). The ISL has two roles: it provides an additional tracking layer to link tracks between SVX-II and the COT and increases the tracking coverage in the forward region between 1< $|\eta| < 2$. All modules use small-angle stereo sensors. For the readout, the SVX3D chip is used again; there are 296 modules altogether.

The L00 detector [3] is located on the inside the SVX-II and is mounted on the beam pipe. It provides another high-resolution tracking point and compensates for a potential failure of the inner layers of the SVX-II due to radiation damage. It consists of two concentric hexagon structures, the so-called wide and narrow sensors. Altogether, there are 72 actively cooled single-sided modules. For L00 the hybrids are not mounted on the sensor but outside of the interaction region. For L00 the same readout chip as for SVX-II and ISL is used.

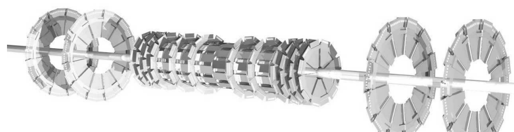

Fig. 2. Sideview of the DØ Silicon Microstrip Tracker

3. The DØ Silicon detector

The DØ Silicon Microstrip Tracker(SMT) [4] has roughly half the sensor area of the CDF silicon detector and consists of 6 barrels with 4 layers [3] . Each layer has two staggered and overlapping sub-layers. Additionally there are two sets of silicon disks, the F and H-Disks (see Fig. 2). For the barrel detector, the sensors in layers 1 and 3 have $r\phi$ and rZ sides in the central barrel and single-sided sensors in the outer barrels. Layers 2 and 4 are made of small angle stereo sensors. All sensors were manufactured by Micron. DØ uses the SVX-IIE chip for readout throughout the SMT. Like the SVX3D it has an analog pipeline front-end, a digital back-end and 128 channels, but is not capable of deadtime-less operation. Altogether, there are 432 modules in the barrel part of the DØ SMT. The 12 F-Disks are located between the individual barrels and as an end module of three disks at each end of the SMT. They consists of small-angle stereo sensors made by Micron and Eurisys. There are 144 modules in the F-Disks altogether. The 4 H-Disks are located up/downstream from the F-Disks to provide tracking up to $|\eta|$ of 3. They consists of two single-sided sensors made by ELMA that are mounted back-to-back. Altogether there are 192 H-Disk modules.

In the 2006 shutdown DØ added an additional layer of silicon inside of layer 1 of the SMT. Its main purposes is to compensate a potential degradation of layer 1 and to provide another precision tracking point before the SMT. The DØ L0 [5] has been operated successfully since June 2006, but as it is a very recent addition, there are no results concerning radiation damage yet.

[3] DØ SMT layers are numbered from 1.

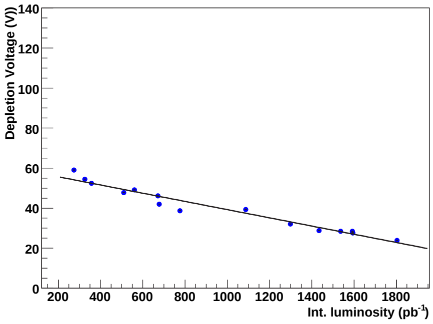

Fig. 3. CDF: Depletion voltage versus luminosity for one module in SVX-II layer 0. This plot includes data up to a delivered luminosity of 1.8 fb^{-1}.

4. Radiation Damage studies at CDF

For the radiation damage studies, CDF focuses mainly on the L00 and the inner layers of the SVX-II, since those are most affected by radiation damage. CDF studies both the evolution of the depletion voltage and the signal to noise ratio (S/N) in the sensors. For the study of S/N, two approaches have been made. CDF both measures the evolution of the bias currents and also studies the S/N using J/ψ data.

4.1. *Bias Voltage Scans*

CDF regularly conducts scans of the depletion voltage of the sensors. Two different approaches are used, the signal bias scan and the noise bias scan. For the signal bias scan the charge of hits on tracks is measured as a function of the bias voltage. For each bias voltage point, the peak of the charge distribution is derived fitting a Landau convoluted with a Gaussian resolution function. Then all these points are fitted using a sigmoid function. The actual depletion voltage of the sensor is then defined as the 95 % amplitude of the fitted sigmoid function. This approach works for all sensors, however the disadvantage of this method is, that it requires beam time. The noise scan uses the dependence of the n-side noise on the bias voltage. It requires the use of double-sided sensors, so it can only be applied to SVX-II or ISL modules. The bias voltage is varied and the depletion voltage is defined as the point where the noise reaches a minimum. The bias scan results for one SVX-II ladder in layer 0 are shown in Fig. 3. CDF assumes that the layer 0 of SVX-II is the most critical layer for the detector lifetime, as L00 is a more radiation tolerant design due to its actively cooled sensors and its ability to work with higher bias voltages. A prediction of the detector lifetime has been made in 2003 [6] and CDF now has accumulated enough data to test this prediction and also to draw conclusions on the point of inversion for layer 0 and the potential lifetime of this layer (see Fig. 4). The current data predict type inversion to take place around 2.9 fb^{-1} and layer 0 of SVX-II to outlast the current Run-II luminosity goal of 8 fb^{-1}.

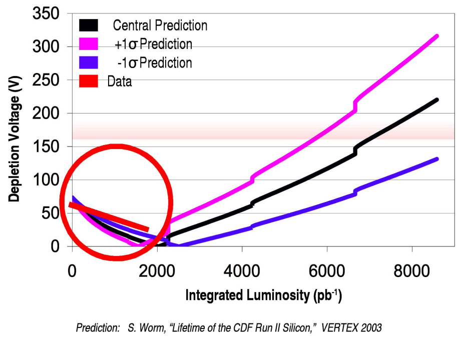

Fig. 4. CDF: The bias scan results for L0. The encircled line indicates the actual depletion voltage evolution with increasing luminosity. The three lines indicate the model predictions as described in [6].

4.2. *Bias Current measurements*

This measurement exploits the fact that the bias current increases linearly with luminosity. CDF uses 95 pb^{-1} of data taken in May/June 2004 for this measurement. The Tevatron beam was slightly off-centred with respect to the silicon during this period, which is taken into account in this study. The main limiting factor for this measurement is the knowledge of the sensor temperature. For the CDF silicon modules the temperature is only measured close to the hybrid at the end of the module. The temperature gradient curve for the entire module had therefore to be derived from a finite element analysis, which lead to large uncertainties. All these effects were taken into account and

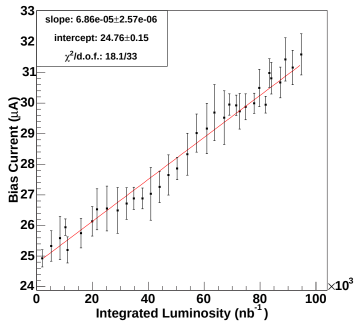

Fig. 5. CDF: The linear dependence of measured bias current with integrated luminosity for the 95 pb^{-1} used in the bias current measurement for a sample ladder.

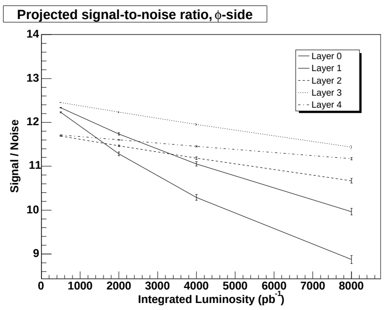

Fig. 6. CDF: Prediction for the S/N evolvement for the entire Run-II using the bias current measurement. All 5 layers of the SVX-II are shown here.

the measured bias currents show the expected linear dependency (see Fig. 5). From the measured bias currents one can derive the particle flux and the leakage current. CDf obtains a flux for the innermost layer of the SVX-II of $10.4 \pm 5.1 \cdot 10^{12}$ particles/cm^2 fb^{-1}. In order to make predictions for S/N evolution of the sensors depending on the luminosity, the model described in [6] was used. The model assumes a constant amount of signal and an increase in the noise in both sensors and electronics both due to the received radiation dose. This allows CDF to make projections for the S/N development (see Fig. 6). The differences between the Hamamatsu ladders (layers 0,1 and 3) and the Micron ladders can be clearly seen, as well as the expected radial dependence of the S/N degradation. Using these predictions, CDF expects no problems with the S/N ratio of its sensors for the entire Run-II.

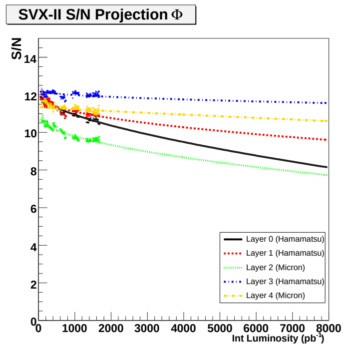

Fig. 7. CDF: Prediction for the S/N behaviour for the entire Run-II using $J/\psi \rightarrow \mu^+\mu^-$ data. All 5 layers of the SVX-II are shown.

4.3. *S/N measurements*

An alternative approach used by CDF is to measured the S/N ratio directly using data from $J/\psi \rightarrow \mu^+\mu^-$ data. In this case the signal charge is measured for hits on tracks and the noise is taken from calibration data taken between stores. For this measurement CDF processes a large fraction of the entire available Run-II dataset which corresponds to 1.7 fb^{-1}. In order to predict the evolution of S/N for the entire Run-II period, a simple model for the luminosity dependence has been used. The signal component is assumed to decrease linearly with luminosity, while the noise is assumed to increase with the square-root of the luminosity. This simple model gives a reasonable description of the data. Using this model CDF makes again a projection of the S/N behaviour for the entire Run-II (see Fig.7). A similar behaviour as for the bias current measurements is seen and again no problems for detector longevity are foreseen.

5. Radiation Damage studies at DØ

The radiation damage studies [7] done at DØ are done in a similar fashion to the ones conducted at CDF. DØ 's main concern for detector longevity is the lifetime of layer 1.

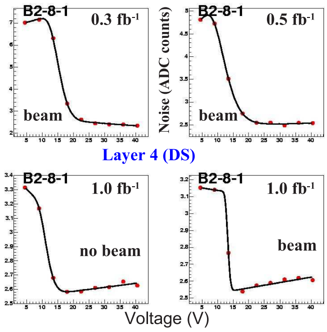

Fig. 8. DØ : Noise Bias scan results with and without beam for a module in layer 4.

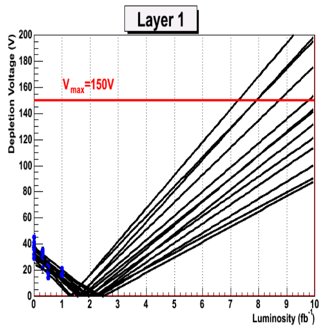

Fig. 9. DØ : Evolution of the layer 1 depletion voltage for the entire Run-II

5.1. *Bias Voltage scans*

DØ conducts both signal and noise bias scans for their sensors. To check the impact on the noise due to beam, they perform noise scans both with and without beam. The results are shown in Fig. 8 covering up to 1 fb^{-1} of delivered luminosity. Using the results from the bias scans, DØ also makes a similar projection for the depletion voltage evolution for the entire Run-II, they predict the point of type inversion to be between 1.5 and 3 fb^{-1} depending on the module and the lifetime of the entire layer 1 to be at least 7 fb^{-1}.

5.2. *Bias Current studies*

DØ also derives the received dose in the SMT using bias current measurements. Additionally, they also have irradiated several SMT modules using the Fermilab 8 GeV Proton Booster. They then measured the depletion voltage of these modules after they have received a well-defined dose. Using the measured dose from the bias current measurements, this provides them with a an additional cross-check for the depletion voltages. DØ obtains a particle flux of $4.0 - 5.3 \cdot 10^{12}$ particles/cm^2 fb^{-1} for layer 1. The spread indicates both the uncertainty of the method and non-uniformity of the radiation field.

6. Summary

Both Tevatron detectors show the expected behaviour and both detectors have not gone through type inversion yet. CDF predicts type inversion for their SVX-II layer 0 around 2.9 fb^{-1} and does not expect any problems due to depletion voltage or S/N for the entire Run-II dataset. DØ predicts the type inversion for their layer 1 to happen between 1.5 and 3 fb^{-1} depending on the module. Layer 1 will last up to least 7 fb^{-1}. A potential degradation of layer 1 can be compensated by the newly added layer 0.

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