CDF/MEMO/TRACKING/CDFR/6373
Version 1.0
March 12, 2003

CDF Run 2A Silicon Detector Damage Assessment[1]

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Abstract

We present measurements of radiation damage to the CDF Run2a silicon detector. These measurements are consistent with predictions based upon Run1 data. We conclude that from radiation damage the present CDF silicon detector will run through the 2 fb^{-1} of Run 2a, as designed, with an expected operational limit of ~ 5 fb^{-1}. We discuss non-radiation damage mechanisms, extrapolate the rate of failures and conclude on the operational lifetime of the silicon detector.

1 Introduction

The ability to perform precision tracking due to the good position resolution of silicon detectors allows one to resolve charged particle tracks originating from heavy flavor decays. The ability to resolve these topologies is a critical component in B, top and the Higgs physics programs at CDF. Because silicon detectors must be placed close to the beam-line, these devices are susceptible to radiation damage both from $p\bar{p}$ collisions and beam losses. CDF's current silicon system is expected to last for approximately 5 fb^{-1}[1], safely beyond the Run2a design specifications of 2 fb^{-1}. Run 2a will deliver 2 fb^{-1}.

During RunIIb the experiments should be able to cope with up to $\sim$15 interactions per beam crossing at the peak luminosity and $\sim$10 interactions on average. The current RunIIa detector was designed to handle up to 5 overlapping events. Simulation studies of the existing detector in a high instantaneous luminosity environment show dramatic deterioration in performance, specifically high fake rates for b-tagging. As is well known the b-tag efficiency and fake rates are critical parameters in new heavy particle searches. The success of the Run2b program relies and benefits greatly from excellent silicon detector performance.

A new silicon detector is proposed to replace the existing detector and is designed to handle the high density tracking environment as well as survive the higher luminosity scheduled for Run 2b. With approximately 135 pb^{-1} delivered to CDF, Run 2a is 6.75% complete. At this point of the run, the following questions naturally arise:

- What is the radiation environment in Run 2a at CDF? Is it consistent with the Run 1 expectation?
- Are the observed effects, if any, from bulk damage to the silicon sensors consistent with this radiation environment?

[1] Submitted, upon request, to Peter Rosen, *Associate Director of the Office of Science for High Energy and Nuclear Physics* on 12/10/02 in consultation with CDF spokespeople and FNAL directorate.

- Are the observed effects, if any, from surface damage to the readout ASICs consistent with this radiation environment?
- Are there any other factors beside radiation damage which may limit the useful lifetime of the Run 2a detector?

We address each of these questions in the following sections.

2 Radiation Damage

The radiation environment at CDF for Run is measured using both dedicated dosimeters and the silicon detector itself. These measurements are discussed in the following sub-sections:

2.1 Radiation Field Measurement

The radiation field inside the CDF tracking volume, near the silicon detectors is measured using thermal luminescent dosimeters (TLDs). Approximately 1000 TLDs of two types are installed at 145 locations in the tracking volume. One type of dosimeter is sensitive to ionizing radiation the second to both ionizing radiation and low energy neutrons ($E_n < 200$ keV). We installed and harvested dosimeters on two occasions. Data from the two exposures allow us to separate the ionizing radiation field into components: one from collisions and another from proton beam losses. The data show that ionizing radiation in the tracking volume is dominated by proton-antiproton collisions and has a radial dependence following a power law in $1/r$, where r is the distance from the beam. Our TLD measurements yield a power law exponent in the range from 1.5 – 1.8 for the region of the silicon detectors and their support electronics. This range of exponents shows a dependence on the distance along the beam line from the interaction point. We also find that the silicon sensors accumulate radiation at a rate of 300 ± 60 rad/pb^{-1} delivered luminosity at a radius of 3 cm from the beam. CDF published results from Run 1A where a power law exponent of 1.5 was measured and the silicon detector located at $r = 2.99$ cm accumulated 300 rad/pb^{-1} [2]. Measurements of the radiation damage in the Run 1A detector also measured a power law radial dependence of $r^{-1.67}$ [3]. Figure 1 shows a comparison of the projected radiation dose for 142 pb $^{-1}$ delivered to CDF based on Run1a TLD measurements, Run1a silicon damage profiles and Run2a TLD measurements. The low energy neutron measurements show a flat distribution in the region of the SVX and ISL, consistent with a model of a "neutron gas" throughout the tracking volume. The radiation levels inside the CDF tracking volume are as expected.

2.2 Radiation Damage to the Silicon Sensors

Radiation damage to the silicon sensor bulk manifests itself in several ways (e.g. increase in reverse biased leakage current, change in depletion voltage). Due to the relatively small dose received so far, CDF is presently most sensitive to an increase in leakage current. As part of its control system, CDF logs the leakage current drawn by the silicon bias voltage power supplies every few seconds. Measuring the leakage current increase as a function of time allows us to monitor the radiation damage incurred by the sensors. Figure 2 shows the ionizing radiation rate in units of fluence (particles/cm2) per unit luminosity delivered to CDF (pb^{-1}) as a function of azimuth (ϕ) for the innermost L00 silicon sensors[2]. The dots represent the calculated radiation rate from L00 leakage current measurements and the curve is an extrapolation from the TLD measurements. The modulation in ϕ is due to a 4 mm offset of the beam relative to the detector axis. The 10% agreement between the TLD and silicon measurements shows a good understanding of the radiation field and damage rates in the silicon sensors. Details of these measurements are presented elsewhere [5].

Currently, we are in the process of updating all our measurements[3] and simulating the radiation environment using Monte Carlo techniques. A detailed article is being prepared for submission to Nuclear Instruments and Methods in the early part of 2003.

[2]For a technical explanation of this measurement choice, see Appendix A

[3]Preliminary analysis suggests that the newer data is consistent with previous measurements.

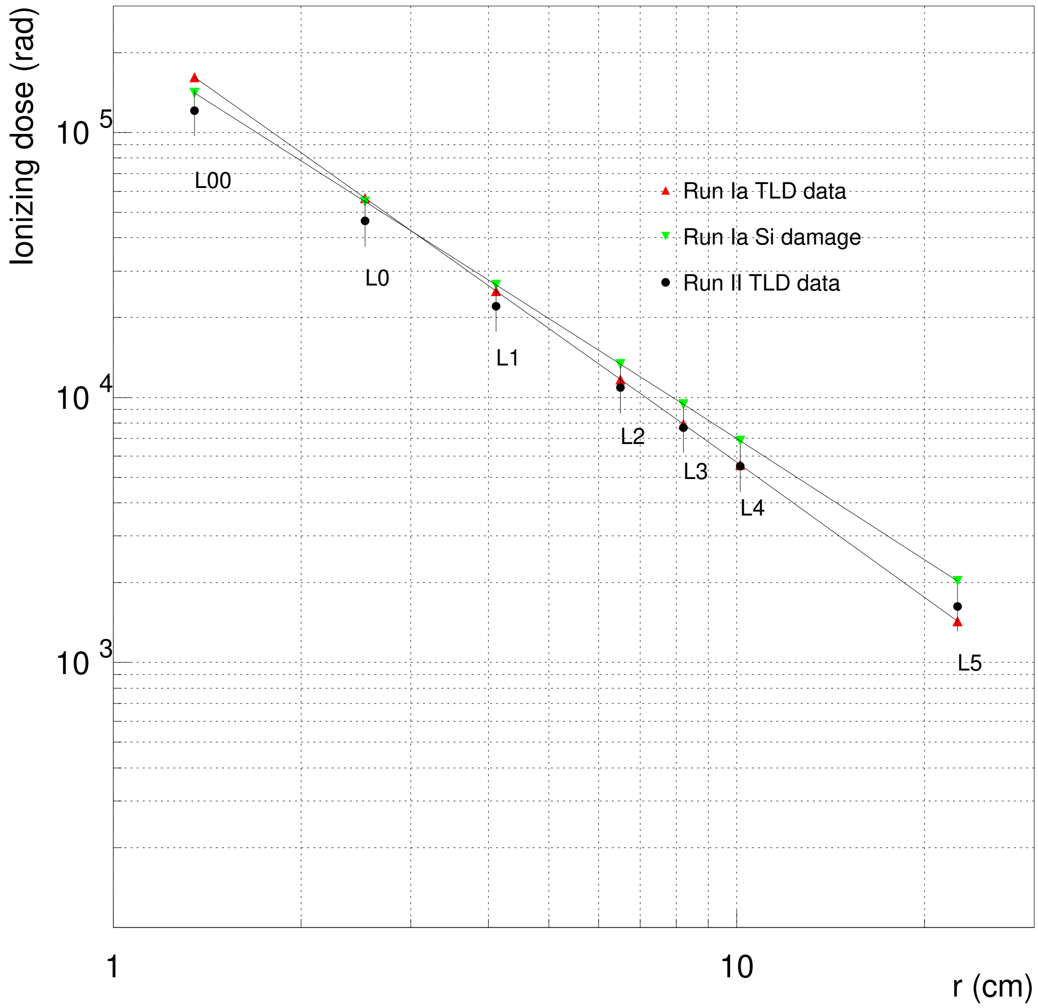

Figure 1: Calculated ionizing radiation dose vs radius for 142 pb^{-1} delivered luminosity. The closed circles is the radiation dose from TLD measurements extrapolated from measurements made with a delivered luminosity of 10.7 pb^{-1}. The curves are from Run 1a published dosimetry data(triangles) [2] and radiation dose inferred from silicon radiation damage profiles measured in Run 1a (inverted triangles) [3].

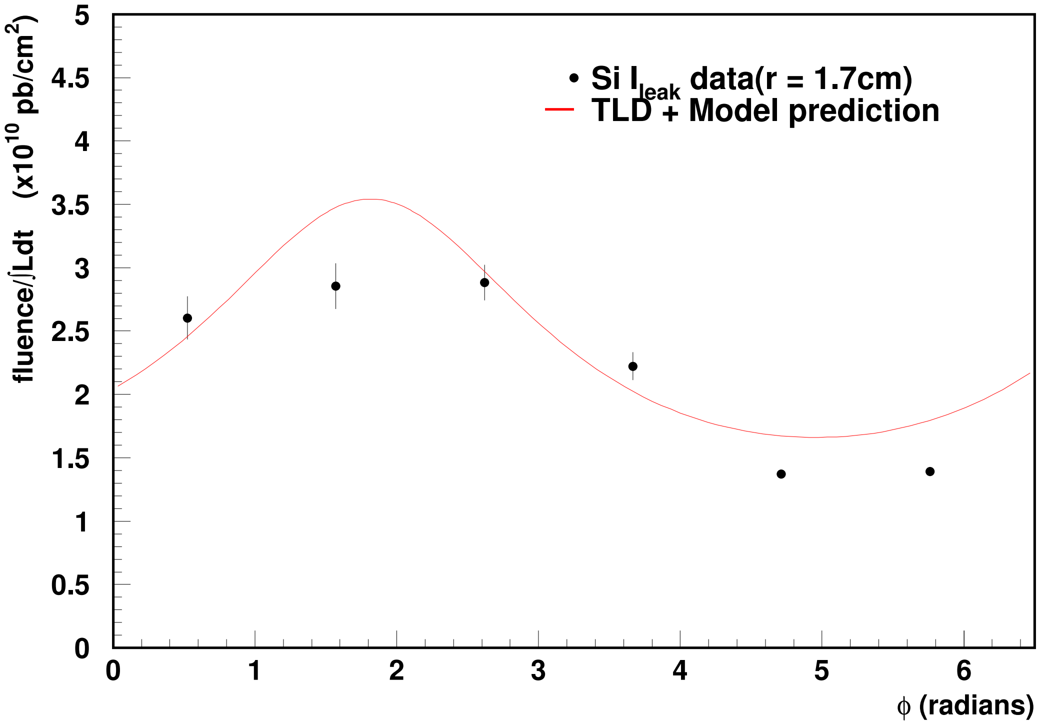

Figure 2: Fluence rate as a function of azimuth (ϕ) for the innermost silicon layer (L00, r=1.7 cm). The dots represent leakage current measurements in the L00 silicon sensors while the curve is from an extrapolation of the TLD measurements to L00.

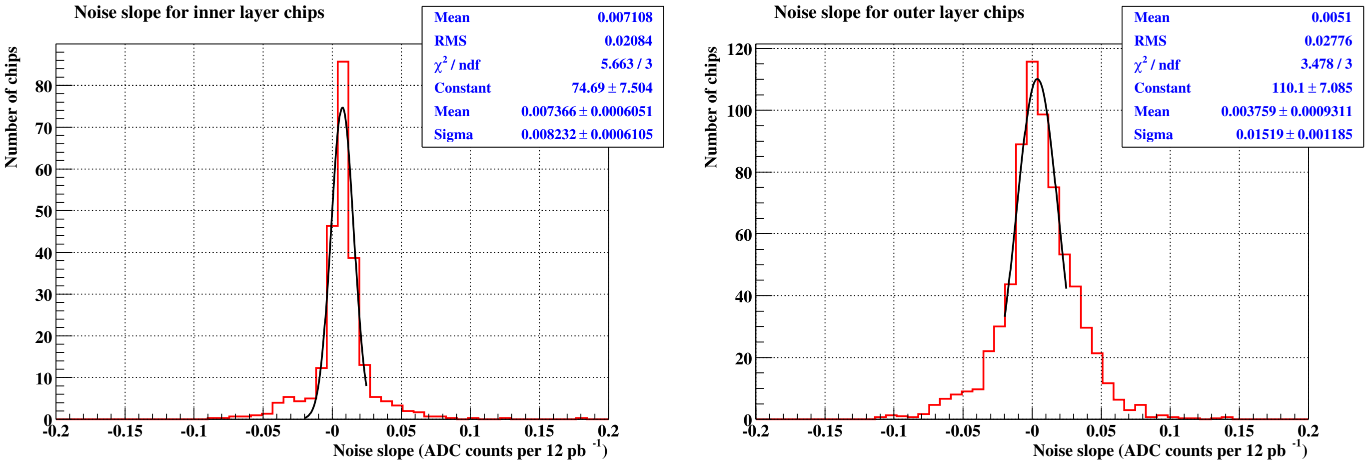

Figure 3: *Fitted slope of noise (ADC counts/12* pb^{-1}*) of innermost(left) and outermost(right) layer of the SVXII detector, measured in calibrations from 2/02 to present.*

2.3 Radiation Damage to the SVX3D chip

Test-beam results show that surface damage to the SVX3D chip result in increased noise and/or shifts in the pedestal [6]. These results show, for example, that a 2 Mrad exposure yields a 20% increase in the pedestal width (noise). During periodic calibrations, the pedestal and pedestal widths (noise) are measured. The rates of noise[4] increase and pedestal shift (ADC counts/12 pb^{-1}) over the period from 2/02 to the present are shown in Figures 3 and 4, respectively. CDF silicon detectors' nominally have a pedestal of 60 ADC counts with a noise of 3 ADC counts. The Figures show distributions of pedestal and noise slopes which are consistent with zero with the exception of the noise slope for the innermost layer. There is no evidence of radiation damage to the SVX3D chip except in the innermost layer where 0.007 ADC/12 pb^{-1} is measured. The innermost layer of SVXII at 2.5 cm has received 50 krad. One would expect 0.5% increase due to SVX3D chip damage. The measured slope gives a change of 0.07 ADC after 135 pb^{-1}, a 2.5% increase, which is a factor of 5 higher than expected from chip damage alone. If one allows for the contributions from sensor damage as well, our measurements are consistent with the measured radiation dose.

3 Component Failures

Unfortunately, radiation damage is not the only damage mechanism which may limit the useful lifetime of CDF's Run 2a silicon detector. CDF silicon has so far experienced several irreparable types of component failures which may be classified by their causes, what part of the silicon system they effect, and whether or not they are irreducible. CDF's silicon system consists of three concentric sub-systems: L00, SVXII, and ISL, as shown in Figure 5. L00 has not experienced any irreparable component failures. ISL has suffered two such failures. SVXII has had more significant component failures. Figure 6 shows the incremental percentage of failures on the SVXII detector from installation (01/01/01) to present. SVXII consists of 5 layers of double-sided silicon detectors. One side provides $r-\phi$ information; the other side provides $r-z$ information. Figure 6 distinguishes between these two sides of the detector for two reasons: The first reason is that $r-\phi$ information is used in the CDF trigger system, the second reason is that component failures have not effected the two sides of the detector equally. Figure 6 shows four curves which are explained below:

- RED is the total percentage of $r-z$ chips that have been permanently damaged.

[4] The noise measured during calibrations includes contributions from both the silicon sensor and the readout electronics. Therefore, this measurement overstates the effect of damage to the SVX3D chip.

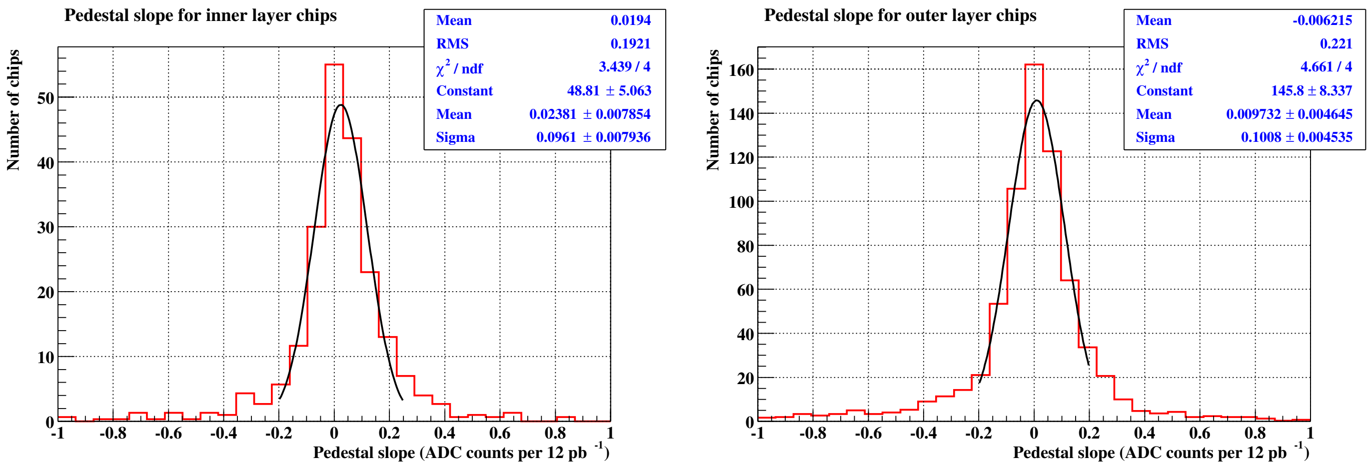

Figure 4: *Fitted slope of pedestal (ADC counts/12* pb^{-1}*) of innermost(left) and outermost(right) layer of the SVXII detector, measured in calibrations from 2/02 to present.*

- BLUE is the percentage of $r-z$ chips that have been permanently damaged by causes that are either not understood or irreducible.
- BLACK is the total percentage of $r-\phi$ chips that have been permanently damaged.
- GRAY is the percentage of $r-\phi$ chips that have been permanently damaged by causes that are either not understood or irreducible.

The GREEN arrows point to the damage induced by the beam incident of 03/30/02 described in sub-section 3.1 below. The PINK arrows point to failures of the DVDD jumper connections due to anomalous trigger conditions as described in sub-section 3.2. These sub-sections also describe counter-measures taken by the FNAL beams division and CDF operations to remove risk of further damage of these types. As a result, these failures do not contribute to the "irreducible" failure rate curves in Figure 6.

The cause of each type of component failure is briefly discussed in the sub-sections below:

3.1 Abnormal Beam Abort

Nine silicon detector modules were damaged as a result of two separate incidents where the beam was aborted abnormally and delivered a high instantaneous flux of particles into CDF. The first incident (3/30/02) occurred as result of total RF failure in the Tevatron which created DC beam and a subsequent quench. The quench triggered the kicker magnets to dump the beam during the abort gap. The abort gap was filled with DC beam and CDF was sprayed with the deflected particles. Seven modules failed during this incident. The second incident (11/09/02) occurred as a result of a false triggering of the abort magnets ("kicker pre-fire"). Two modules failed during this incident. Since the incident on 11/09/02, two additional kicker pre-fires have occurred with no damage was incurred by the silicon. We have taken steps to reduce the likelihood of abnormal beams aborts and their potential damage to CDF silicon. The RF system is now interlocked such that a significant RF failure results in a beam abort in less than 1 micro-second. The rapid response of the abort ensures that the kicker magnets ramp to full field well before beam has had a chance to accumulate in the abort gaps. For the case of the kicker pre-fire, an additional collimator has been installed to intercept the aborted beam before it reaches CDF. A task force has been formed within the beams division to assess the problem and determine optimal short and long-term solutions. Until such solutions are implemented, there is a risk of further damage to the CDF silicon detector from kicker pre-fires. In principle, CDF's silicon system is also susceptible to damage from "kicker miss-fires"

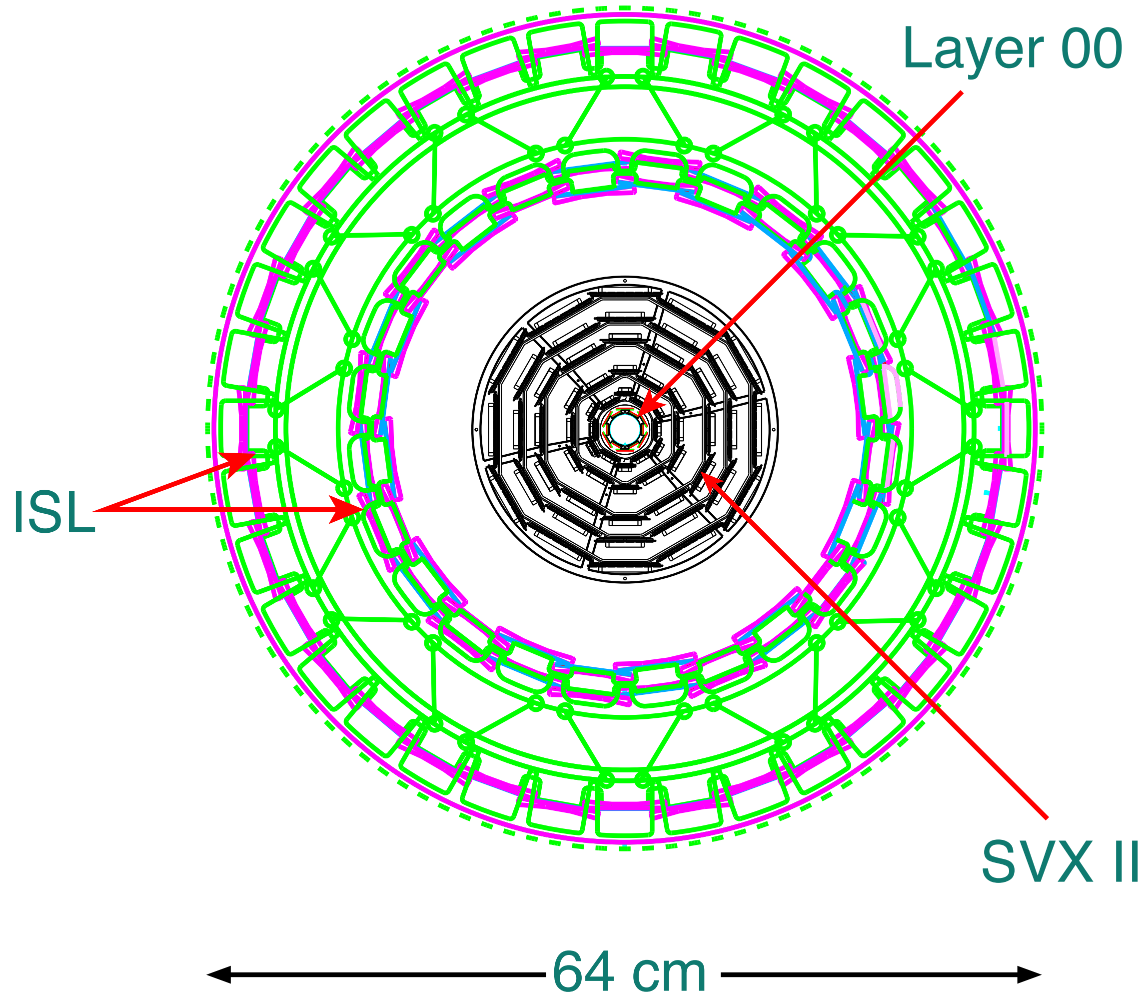

Figure 5: *End-view of CDF Run 2a silicon system.*

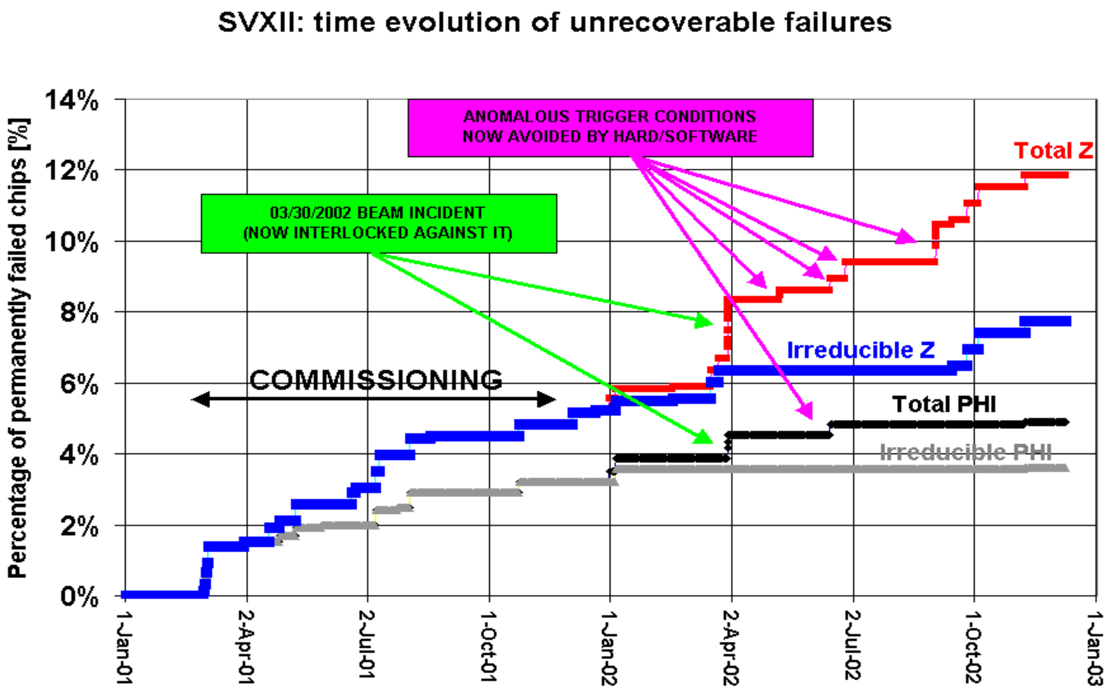

Figure 6: *SVXII permanent failures versus time.*

where some number of the 10 kicker magnets fail to energize when an abort is pulled. No silicon detector modules have been damaged by this mechanism so far.

3.2 Anomalous Trigger Conditions

Fourteen silicon detector modules were damaged, where the time-stamp of the failure is strongly correlated with accidental or intentional operation of the detector in abnormal trigger conditions. These damaged modules can be classified into two types: "DOIM" failures (2) which result in the total loss of the device and "DVDD jumper" failures (12) which result in the loss of r-z information only. The latter type of failure (and possibly the former) is explained by wire-bond breakage. The wire bonds break as a result of fatigue at their heal caused by resonant motion from oscillating Lorentz forces on the wire. A task force was formed within the CDF to study this damage mechanism. Their work is documented in detail on the web[7]. As a result of this work, CDF has modified its operational procedures to avoid further wire-bond damage. Steps taken include:

- Reduction of nominal current which flows through the DVDD jumper bonds.
- Reduction of peak current which flows through the DVDD jumper bonds by increasing readout thresholds and eliminating anomalously high-occupancy situations.
- Imposition of limit on rate (12 kHz) at which the CDF trigger can readout the silicon detector so as to avoid resonant frequencies.

Despite the steps taken by CDF to eliminate recurrence of this type of failure, the extent of bond fatigue induced before the problem was identified is unknown.

3.3 Infant Mortality

Twenty-six silicon detector modules were damaged during installation and/or initial operation. Improvements in operational procedures and/or burn-in have eliminated the occurrence of these failures. These failures may be described as "infant mortality" and are not expected to limit the useful lifetime of the detector.

3.4 Extrapolation

Figure 7 shows the same data points as in Figure 6, with a fitted function super-imposed for each of the curves. The horizontal axis is extended to the end of 2008. The best fit for all the curves is achieved with a logarithmic function, except for the RED (total percentage of failed $r-z$ chips) which is best fit by a linear interpolation. The GRAY and BLUE curves depict best-case scenarios. According to this scenario, the useful lifetime of the Run 2a silicon detector will be determined solely by radiation damage. The BLACK and RED curves depict worst-case scenarios[5]. In this scenario, the silicon detector's $r-z$ capability will be strongly compromised by the end of 2004, independent of radiation damage. It should be noted that the uncertainty on these extrapolations is large.

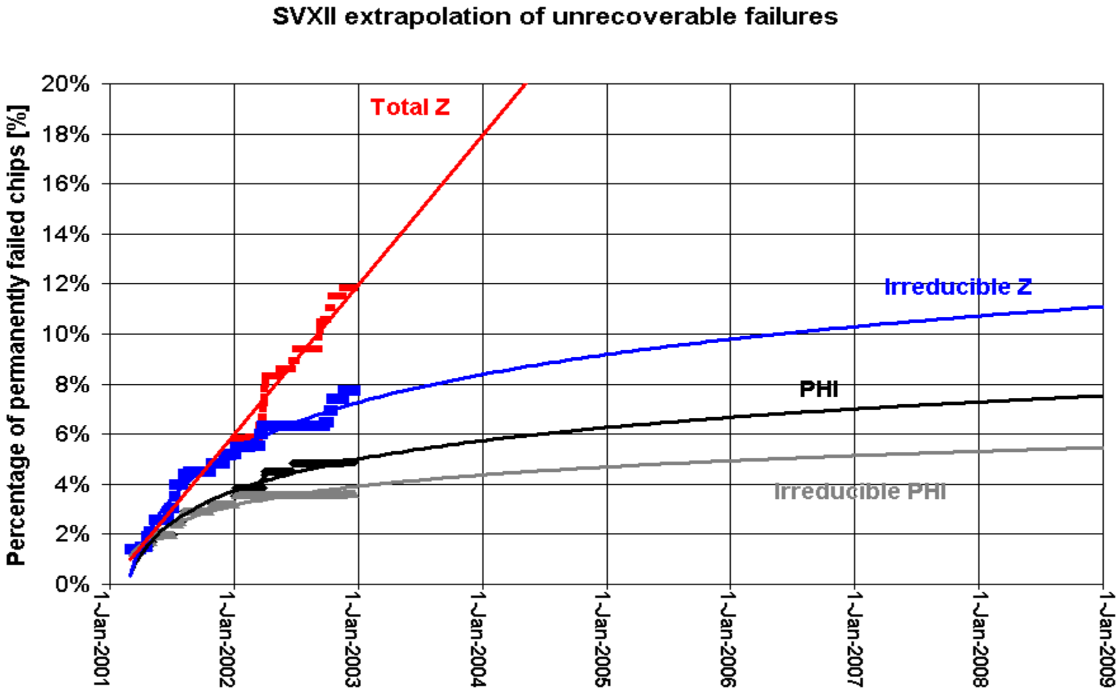

Figure 7: *Extrapolations of SVXII permanent failures versus time up to January* 1^{st} *2009.*

4 Conclusions

After approximately 135 pb^{-1} of delivered luminosity in Run2, we find the radiation in the region of the silicon detectors is consistent with expectations based on Run 1 measurements. Radiation damage to both the sensors and readout chips are also consistent with the observed radiation and expectations from test-beam measurements. Therefore, from radiation damage alone, we expect the SVXII detector to operate up to $\sim$ 5 fb^{-1}, well above the Run2a design goals. However, unanticipated damage mechanisms, discussed above, are important additional factors in estimating the useful lifetime of the CDF Run 2a silicon detector.

Unanticipated damage mechanisms discussed above will reduce the lifetime of the detector below that expected from radiation damage alone. These mechanisms are more difficult to quantify. We

[5]It is assumed that no new failure modes will appear in the time scale of the extrapolation

designed the silicon detector asumming a 2-3 year running period for Run2a, and we expect to meet the goals of efficient operation during that period. However, we do not expect this detector to operate efficiently for a period substantially longer than the design lifetime.

A Technical Details on Leakage Current Measurement

The choice of L00 for the comparison described previously is motivated by several technical issues: sensitivity of the leakage current measurement to radiation damage, amount of radiation exposure and understanding of the temperature profile for the silicon.

The reverse biased leakage current in silicon arises from four main sources:

1. Currents through the bulk silicon due to thermal excitation of electrons and holes into the conduction band.
2. Surface currents between the P and N regions of the silicon due to resistive materials on or embedded in the silicon surface. The current from this source depends, in detail, on the preparation of the sensor surface and whether the sensors are single or double sided.
3. Radiation damage incurred on the surface of the sensors. The current from this source also depends on the surface preparation and on the type and number of structures on the surface.
4. Radiation damage incurred in the bulk of the silicon sensors. The leakage current from this source depends on the amount of modification of the silicon crystalline structure (e.g. displacement of a silicon atom from its nominal location in the crystal lattice and attending modification of the local band structure).

The first two sources produces an irreducible leakage current. The later two sources depend on the radiation exposure. Radiation damage to the surface dominates at low doses (below 10krad) and depends on the type of radiation. Radiation damage to the bulk dominates at higher doses (above 100krad) and is independent on the type of radiation. All of these contributions are temperature dependent.

Because all of the above contributions depend on the temperature of the silicon, a detailed knowledge of the temperature profile of the silicon sensors is necessary. The L00 sensors are in contact along their entire length with a heat sink making the thermal profile simple and constant. The remaining silicon sensors are in thermal contact with their heat sink only at one end. In addition a heat load is located set near the heat sink. This form of heat removal from the sensor induces a thermal gradient which must be correctly accounted for. Further, temperature sensors are located at only a few locations on the silicon support structures which form part of the heat sink.

At the time of the study which produced Figure 2, the accelerator had delivered 30pb^{-1} to CDF. This implies a dose of 35krad for L00 and 10krad for L0. Being single sided and having a uniform temperature profile means that corrections necessary to calculate the charged particle fluence are smaller and better understood for L00 (at these doses) than for the remaining silicon.

References

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