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Operational Experience and Performance of the CDFII Silicon Detector

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Abstract

The CDFII silicon detector consists of 8 layers of double-sided silicon micro-strip sensors totaling 722,432 readout channels, making it one of the largest silicon detectors in present use by an HEP experiment. After nearly two years of data taking, we report on our experience operating the complex device. The performance of the CDFII silicon detector is presented and its effect on physics analyses is discussed. The CDFII silicon detector has begun to show measurable effects of radiation damage. These results and their impact on the expected lifetime of the detector are briefly reviewed.

Key words: CDFII, SVXII, ISL, L00, silicon
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1 Introduction

The Collider Detector at Fermilab (CDF) completed a major detector upgrade for the start of Run 2A of the Tevatron in March, 2001. The upgraded detector (CDFII) is described in detail elsewhere[1]. A significant component of this upgrade was a substantially larger silicon detector. The new silicon detector consists of 8 layers of double-sided silicon sensors divided into three sub-systems, SVXII and ISL, and L00. Commissioning of the CDFII silicon detector was completed in June 2002. This long commissioning period was due in part to the inherent large scale and complexity of the system, but was also due to several significant technical problems which had to be overcome. These problems their solutions are described in detail elsewhere[2].

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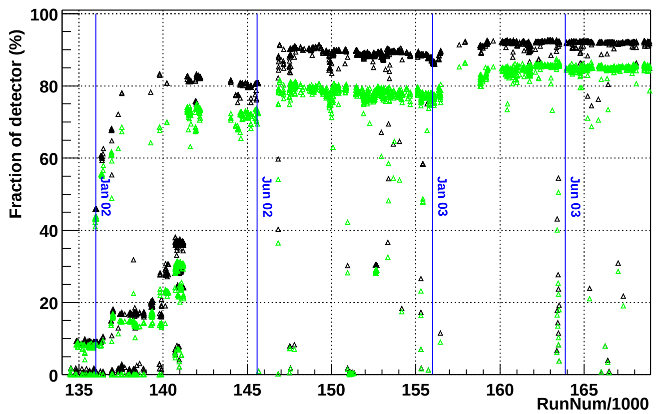

Fig. 1. *Silicon commissioning progress versus time. The black dots are the fraction of the detector operating for each run, the green dots are the fraction of the detector operating and producing data with less than 1% errors.*

2 Operation

Since the completion of the commissioning phase, the CDFII silicon system has been reliably recording physics quality data with 92.5% of modules as shown in Figure 1. Stable operation of the detector was achieved through a vigilant program of monitoring, maintenance and repair of relatively ordinary problems of the kind one might expect from a system of its size and complexity. In addition, two rather extraordinary problems were encountered during this operational period which also had to be addressed to maintain performance levels necessary for physics quality data.

2.1 High Dose-Rate

The first of these unexpected phenomena was the failure of 9 silicon modules in two separate incidents in which the detectors received anomalously high dose-rates from the Tevatron. The first incident occurred March 30, 2002 as a consequence of a simultaneous failure of all Tevatron RF cavities. Three RF stations (2 proton, 1 anti-proton) did not stay off as is the design in such a failure, but rather came back up out of phase and de-bunched the beam. After several seconds of high proton losses, magnets quenched, and the beam was aborted. Since the beam had lost its bunch structure, the abort gaps were filled with particles so when the abort fired, the "kicker" magnets responsible for diverting the beam into a dump deflected these particles into CDF while ramping up to full field. Combining the rise-time of these magnets with geometry between them and the limiting aperture of CDF it is deduced that this exposure delivered a particle flux $\geq 10^7$ MIPs/cm^2 in a period of time

≤ 150 ns. As a result of this exposure, at least[1] 6 SVX3D chips were damaged in a very specific way. Symptomatically, the damaged modules behaved as if they had lost power to the analog front end of the chip. The second incident involved an accidental Tevatron abort due to spontaneous breakdown of the thyratron used to switch on the kicker magnets. This type of failure, known colloquially as a "kicker pre-fire," will cause zero, one, or two beam bunches to be deflected into CDF, depending on the timing of the pre-fire relative to the bunch orbital frequency. On November 9, 2002 one such kicker pre-fire occurred causing the failure of two SVX3D chips with symptoms identical to those that failed in the other high-dose rate incident.

Experiments were performed in which the high particle flux was replicated (and exceeded) in a controlled environment. These included two separate 8 GeV proton irradiations. The damage to the SVX3D chips, however, was not reproducible.

Lacking a causal understanding of the damage mechanism, we sought to prevent further occurrence of high dose-rate situations and mitigate the particle flux through CDF in the event that they do transpire. The former was accomplished by implementing a fast interlock which aborts the beam if RF failure occurs before the beam has had time to de-bunch. The latter was achieved by positioning collimators between CDF and the kicker magnets to intercept deflected particles. With these counter-measures in place no additional chips have been damaged despite the occurrence of several RF failures and kicker pre-fires.

2.2 Wire-bond Failure due to Resonant Lorentz Forces

The second of these unexpected phenomena was the failure of 14 silicon modules in several incidents where CDF was operating under anomalous trigger conditions. These failures were symptomatically consistent with the loss of the digital power lines through the jumper[2] of the SVXII hybrid readout electronics. These symptoms were reproduced unambiguously on test pieces by removing the digital power bond. Hypotheses as to the cause of the electrical failure such as fusing wire-bonds due to excess current draw and accelerated aging of the vias were investigated and ruled out. Upon the realization that the wire-bonds in question were oriented orthogonal to CDF's 1.4T magnetic field, it was conjectured that Lorentz forces causing mechanical stress might

[1] The chips are readout serially. A damaged chip masks knowledge of the state of chips further down the daisy-chain.

[2] The jumper is a passive board, consisting only of wire-bonds, traces, and vias that route power, control signals, and data from the r-phi side electronics to the r-z side electronics of the double sided modules in the SVXII detector sub-system.

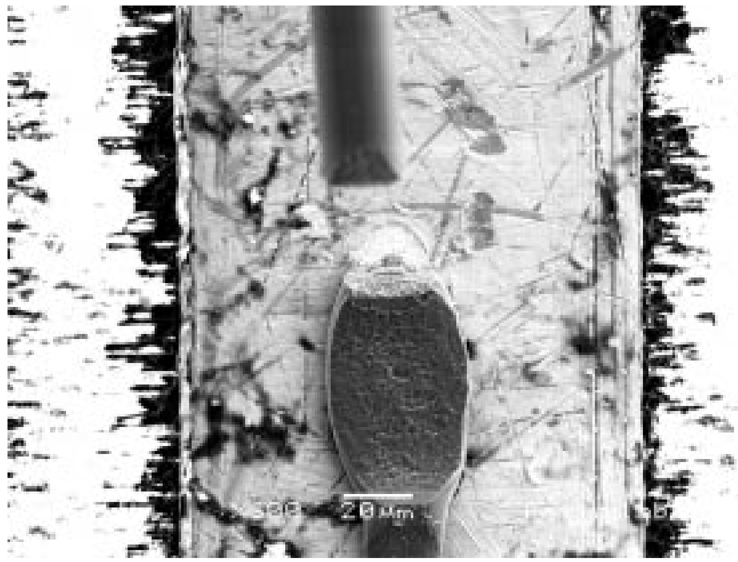

Fig. 2. *SEM picture of wire-bond broken by resonant Lorentz forces.*

be the cause of bond-failure. This idea was strengthened with the realization that current would pass through the jumper's bonds each time a trigger was issued and could possibly excite a resonance. A simple calculation found that for a 2mm diameter aluminum loop wire-bond, the fundamental resonance would occur at $\sim$ 15 kHz. This number was astonishing since some of the failures mentioned above had occurred when running CDF intentionally (to test trigger throughput) at a fixed rate of $\sim$ 16 kHz. The resonant Lorentz force hypothesis provided a connection between anomalous trigger conditions and a failure mechanism. The hypothesis was confirmed by placing both test bonds mimicking those of the jumper in a 1.4T field and pulsing them with a few 100 mA AC current similar to that which would pass through them as part of the readout cycle. Resonance was observed in the test bonds with a video camera. Bond failure resulted after minutes of exposure to resonance. The failed bonds were analyzed under SEM and found to be consistent with fatigue stress at the foot of the bond. A picture of one such broken bond is shown in Figure 2. The experiment was repeated with spare SVXII ladders driven by the CDF DAQ with the same outcome. It was concluded that resonant Lorentz forces were the cause of the wire-bond failures, but since some of the failures had occurred during normal data taking the question remained: how does one get a resonance out of a system that is triggered randomly by indeterminate physics processes? This seeming paradox was resolved by observing that if the silicon-detector were to have any one of its thousand or so modules behave in a way that 100% of its channels were always being readout instead of just those over threshold and its readout time was longer than the time between subsequent triggers a resonance could (and indeed apparently did) occur.

Upon the discovery of the resonant Lorentz force failure mechanism, the CDF

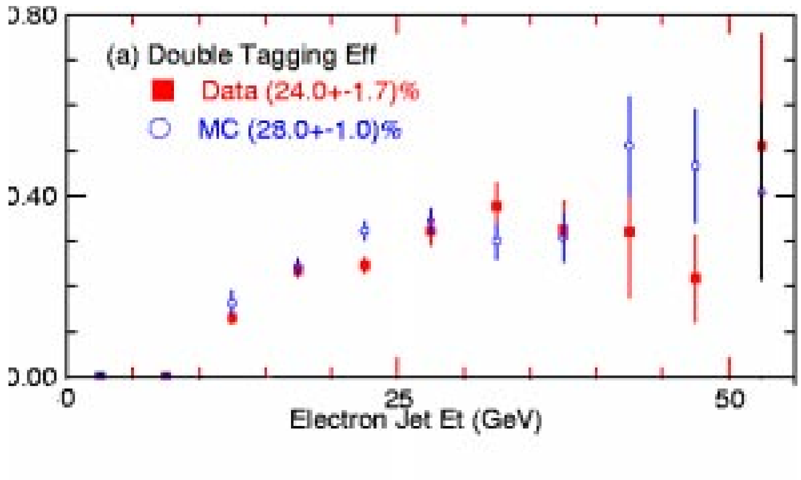

Fig. 3. *Double b-tag efficiency for data (red) and Monte Carlo (blue) as a function of jet* E_T.

silicon group modified its operational procedures to avoid further wire-bond damage. Steps taken included the reduction of digital current consumption, elimination of high-occupancy situations, the installation of monitoring software to recognize anomalously high-occupancy situations and automatically issue the appropriate reset commands, and ultimately the design, commissioning, and installation of electronics which perform a FFT (fast Fourier transform) on the silicon readout commands, directly inhibiting further triggers from being issued if a resonance is detected. With these protection and mitigation mechanisms in place, no addition silicon module jumper failures have been observed.

3 Performance

The performance CDFII silicon detector as well as its successful use in an innovative on-line displaced track trigger (SVT) have been measured and are discussed in detail elsewhere[3] and [4]. The signal-to-noise ratio ranges from 14:1 for the $r-\phi$ side of SVXII to 10:1 for L00. The best position resolution achieved is 9 μm which is for two-strip clusters in SVXII. The average offline tracking efficiency is 94%. SVT online tracking efficiency is over 80%. No degradation in performance has yet been observed in the two years of operation. On the contrary, performance continues to increase as alignment, clustering and tracking algorithms improve.

3.1 Secondary Vertex Tagging

One of the principal functions of the CDFII silicon detector is to detect secondary vertices resulting from the decay of b quarks. Indeed, many of the improvements in the design of this detector relative to its predecessor were specifically aimed at improving b-tag efficiency. The double b-tag efficiency currently achieved at CDF approaches 40% for energetic jets (see Figure 3). This amounts to a 55% event tag rate for a $t\bar{t}$ event, which is already better than that which was achieved at the conclusion of Run I. This efficency will increase as the full power of the new silicon system is utilized. Tracks used in the vertexing algorithms are currently limited to those that originate in the drift chamber which only has coverage to $|\eta| = 1.1$. The use of tracks recontrsucted soley with the silicon detector, exploiting the forward coverage of ISL, will allow tagging out to $|\eta| = 2$. Moreover, there is visable degradation of the measured tag rate in the regions where SVXII has gaps and/or passive material. This will be compensated for when L00 is used for tagging.

L00 was designed to recover degraded impact-parameter (IP) resolution due to multiple scattering off passive material in SVXII. L00 only recently has been aligned sufficiently to see this effect. By selecting tracks that pass through this material region with and without L00 hits attached, the improvement in IP resolution provided can be seen in Figure 4. The effect is largest at low P_T where multiple scattering effects are the dominant component of IP uncertainty. It should be noted that current L00 hit efficiency is only 65% as a result of aggressive clustering cuts. This number, however, does not include the effects of the substantial fraction of overlapping strips in the L00 design. Moreover, it should get better with final alignment and optimized clusetruing.

3.2 Forward Tracking

The forward silicon layers of ISL allow tracking where there is no drift chamber coverage. Pattern recognition difficulties can be avoided by seeding the track using information from the calorimeter. A helix is formed using the cluster centroid as one endpoint and the primary vertex as the other with the curvature being obtained from the energy in the calorimeter under the assumption that the electron is massless and thus is equal the momentum. Such an algorithm has been successfully implemented in CDF. Efficiencies in excess of 70% have been achieved out to $|\eta| < 2$ with minimal fake rates.

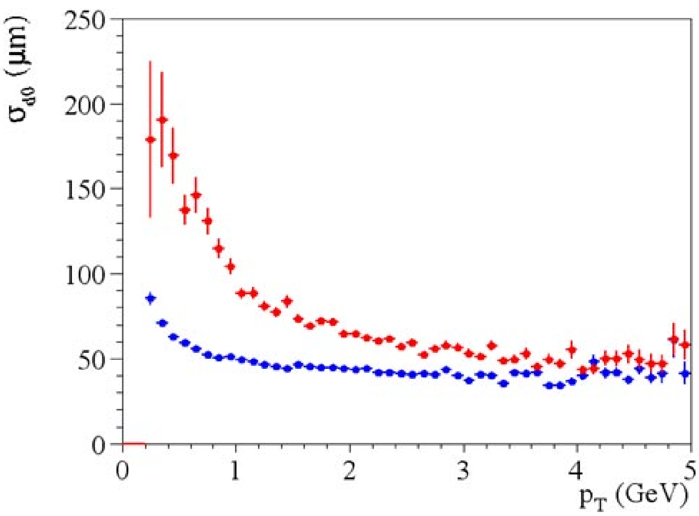

Fig. 4. *The impact parameter resolution is shown as a function of p_T for tracks traversing passive material in SVXII, with (blue) and without (red) use of L00 hits.*

3.3 Physics Results

CDF is producing physics results utilizing the improvements afforded by the new silicon system. There have been numerous recent physics results exploiting SVT. SVT allows CDF to trigger on hadronic B decays for the first time. This has led to the first observations of $\Lambda_b \to \Lambda_c \pi$ (shown in Figure 5) and $B^0 \to KK, B_s^0 \to D_s \pi$.

CDF is also producing high-P_T physics results employing its new silicon detector. Measurements of the production cross-section and mass of the top quark have relied on the b-tagging described above. Other analyses have benefited from the forward tracking provided by ISL which increases their acceptance for electrons. This is most important for analyses with multi-lepton final states and/or statistically limited measurements. The top dilepton cross-section measurement performed this summer by CDF is an example which meets both these criteria. The result of this measurement was a cross-section of $\sigma_{t\bar{t}} = (7.6 \pm 3.4 \text{ stat} \pm 1.5 \text{ syst})$ pb which is $\sim 30\%$ more precise than the Run 1 measurement despite having about the same luminosity.

4 Detector Lifetime

CDF has had 326 pb^{-1} delivered luminosity. With this dose, radiation damage effects have been observed. An increase in sensor leakage current has been

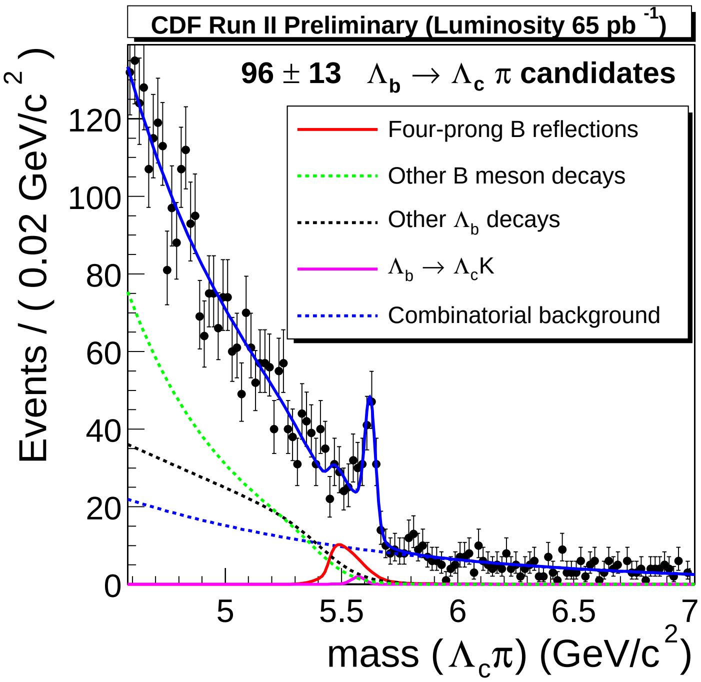

Fig. 5. *Plot showing evidence for the first observation of the hadronic decay, $\Lambda_b \to \Lambda_c\pi$ which was made possible by SVT, CDF's innovative on-line displaced track trigger.*

measured. Using a damage constant of $3.0 \pm 1.0 \times 10^17$ A/cm, fluence as a function of radius has been computed. These results and their comparison to simulations and Run 1 data are discussed in detail elsewhere[5]. This work predicts that CDFII will die from radiation damage if the Tevatron reaches its design goal of 8 fb^{-1}. However, if the Tevatron only achieves its base luminosity goal of 4 fb^{-1}, the detector is expected to survive Run 2 - which will be necessary since the silicon upgrades for Run 2b were recently canceled by the Fermilab director.

5 Conclusion

The CDFII silicon detector has been performing well and operating stably since June 2002. Unexpected component failures were observed. Countermeasures have been taken and no additional failures have occurred since November 2002. Physics analyses are producing results which exploit some of the new capabilities of this silicon detector. Radiation damage effects are measurable and being studied. With all known failure modes seemingly addressed, it is expected that the CDFII silicon detector will continue to produce physics quality data for many years to come.

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