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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 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 impact on physics analyses is discussed. We have already observed measurable effects from radiation damage. These results and their impact on the expected lifetime of the detector are briefly reviewed.*

Keywords *– CDFII, SVXII ISL, L00, silicon*
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I. INTRODUCTION

The Collider Detector at Fermilab (CDF) completed a major detector upgrade for the start of Run 2 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. Commissioning of the CDFII silicon detector was completed in June 2002. This long commissioning period was due to the large scale and complexity of the system, in addition to several significant technical problems which have been overcome [2].

II. THE CDFII SILICON VERTEX DETECTOR

The 8 layer, 704 ladder, 722432 channel CDFII silicon detector consists of three subdetectors: SVXII, ISL, and L00 (``Layer Zero Zero").
SVXII is 360 double-sided ladders in a layout of six 15 cm axial sections times twelve 30 degree φ slices times five radial layers between 2.5 and 10.6 cm. ISL fills the volume between SVXII and the CDF wire tracker (COT), with 296 double-sided ladders at radii of 20 or 28 cm, in total 1.9 m long, providing silicon hits out to pseudorapidity of $|\eta|<2$. L00 is a single-sided layer of 48 ladders mounted directly on the beampipe, 1.5 cm from the beamline, which enhances the impact parameter resolution . The r-φ and r-z views of the detector are shown in Figure 1.
The three subdetectors share the same readout system. It starts with the SVX3D chip, a custom designed ASIC with a 128 channel times 46 capacitor analog storage ring, which makes it possible to acquire data in a ``deadtimeless" fashion, integrating charge on one capacitor while reading out another.

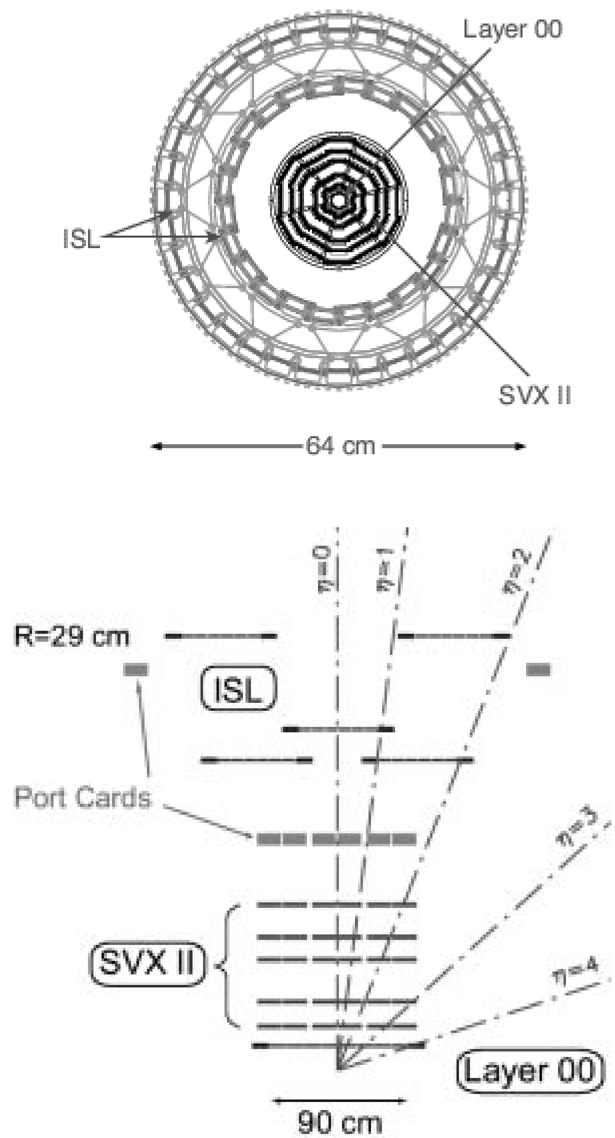

Figure 1: r-φ and r-z perspectives of the Silicon detector, showing all sub-components. Note the compression of the z scale.

The SVX3D chip also reduces the noise and acquisition time by sparsifying channels. Both of these contribute to optimize charge collection.

A wedge of up to 5 ladders is serviced by one portcard mounted near the detector which provides a 1->5 fanout of electrical control signals and converts the data from electrical to optical for transmission out of the detector, a distance of 15m, as well as bringing in the analog, digital, and bias voltages to the chips and ladders.

Behind this is a VME based data acquisition system which controls the entire detector and presents data to the Level 2 and Level 3 trigger systems. The subdetectors share the same power distribution, cooling, interlock, and radiation protection systems.

III. OPERATION

Since the completion of the commissioning phase, the CDFII silicon system has been reliably recording physics quality data with 92.5% of modules. Stable operation of the detector was achieved and is maintained through an aggressive 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 unexpected problems were encountered during initial operation which have been addressed to maintain performance levels necessary for physics quality data.

IV. HIGH DOSE RATE

The first of these problems 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 as a consequence of a simultaneous failure of all Tevatron RF cavities. It was estimated that the exposure delivered a particle flux $>10^7$ MIPs/cm^2 in less than 150 ns. As a result, at least 6 SVX3D chips were damaged. The chips are readout serially, so a damaged chip prevents communication with chips further down the daisy-chain. 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 (``kicker pre-fire”) causes beam bunches to be deflected into CDF, depending on the timing of the pre-fire relative to the orbital position of the bunches. In November, 2002 a 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 on the bench with high particle flux. These included two separate 8 GeV proton irradiations. We were unable to reproduce the damage on the SVX3D chips.

Lacking understanding of the damage mechanism, we sought to prevent further occurrence of high dose-rate. This was achieved by implementing a fast interlock which aborts the beam if RF failure occurs before the beam has had time to de-bunch and by positioning collimators between CDF and the kicker magnets to intercept deflected particles.

V.WIRE-BOND FAILURE DUE TO RESONANT LORENTZ FORCES

The second unexpected phenomenon was the failure of 14 silicon modules in several incidents where CDF was operating under anomalous trigger frequency. These failures were consistent with the loss of the digital power lines through the jumper of the SVXII hybrid readout electronics The jumper is a passive board, consisting only of wire-bonds, traces, and vias that route power, control signals, and data from the r-φ side to the r-z side electronics of the double sided modules in the SVXII detector sub-system. The symptoms were reproduced on the bench 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 realization that the wire-bonds in question were oriented orthogonal to CDF's 1.4T magnetic field, we hypothezised that Lorentz forces causing mechanical stress might be the cause of bond-failure. The fact that current passes through the jumper bonds each time a trigger is issued and could excite a resonance strengthened the assumption.

A simple calculation showed that for a 2mm high aluminum loop wire-bond, the fundamental resonance would occur at ~15kHz. Some of the failures mentioned above had occurred when running CDF intentionally (to test trigger throughput) at a fixed rate of ~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 an 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.

Upon the discovery of the resonant Lorentz force failure mechanism, the CDF 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. We installed electronics to 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 in place, no additional silicon module jumper failures have been observed.

Figure 2: SEM picture of wire-bond broken by resonant Lorentz forces.

VI. PERFORMANCE

The performance CDFII silicon detector as well as the use of its data 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 rφ 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, defined as placing three silicon hits on a track that passes through three active layers of silicon, is 94%. The SVT online tracking efficiency is over 80%. No degradation in performance has yet been observed in the two years of operation. Performance continues to increase as alignment, clustering and tracking algorithms improve.

VII. SECONDARY VERTEX TAGGING

One of the principal functions of the CDFII silicon detector is to detect secondary vertices resulting from the decay of the heavy b quarks. 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. This amounts to a 55% event tag rate for an event that contains a top pair decay, which is already better than that which was achieved at the conclusion of
Run I.
L00 was designed to recover degraded impact-parameter resolution due to multiple scattering off passive material in SVXII. By selecting tracks that pass through this material region with and without L00 hits attached, the improvement in impact parameter resolution provided can be seen in Figure 3.

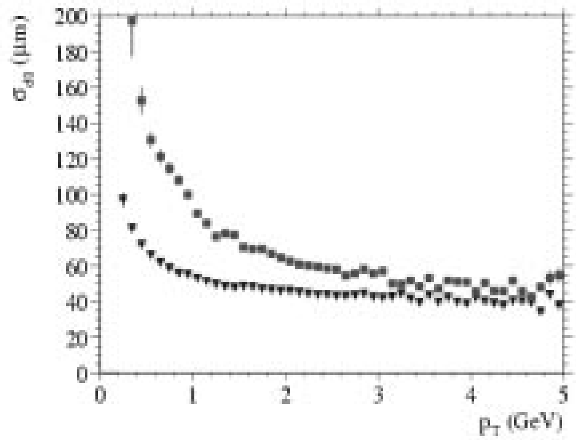

Figure 3: The impact parameter resolution is shown as a function of transverse momentum for tracks traversing passive material in SVXII, with (blue triangles) and without (red squares) use of the L00 hits.

The effect is largest at low transverse momentum, where multiple scattering effects are the dominant component of the impact parameter resolution.

VIII. PHYSICS RESULTS

CDF is producing physics results using the improvements to the 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 Λ_b-> $\Lambda_c\pi$ (shown in Figure 4) and
B^0->KK, B^0_s ->$D_s\pi$.

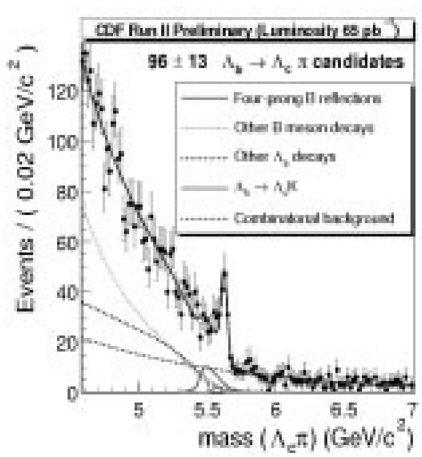

Figure 4: Observation of the hadronic decay Λ_b-> $\Lambda_c\pi$ using the on-line displaced track trigger (SVT).

CDF is also producing high-p_t physics results using 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.

IV. DETECTOR LIFETIME

Approximately 425 pb^{-1} delivered luminosity have been delivered to CDF. The observed increase in leakage current as a function of radius has allowed us to extract a damage constant of 3.0 x 10^{17}A/cm. These results and their comparison to simulations and Run1 data are discussed in detail elsewhere[5]. This work confirms that, as in the models we used to predict the lifetime, the CDFII silicon detector will survive 4 fb-1, but will likely be severely damaged if 8 fb^{-1} is delivered.

V. CONCLUSION

The CDFII silicon detector has performed well and operated stably since June 2002. Unexpected component failures were observed. Counter-measures have been taken to protect the silicon detector. Physics analyses are producing results which exploit the new capabilities of this silicon detector. Radiation damage effects are measurable and are 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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