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Radiation Damage Issues for the SVX II Detector

M. A. Frautschi
The New Mexico Center for Particle Physics
The University of New Mexico
Albuquerque, NM 87131

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Abstract

The upgrade of the Silicon Microvertex Detector for the CDF experiment, SVX II, in the context of the increased luminosity regime of Run II of the Fermilab TeVatron is described. An overview of current literature and experience is presented with recommendations that the practices of online monitoring of the delivered dose be continued, and the possibility of cooling the detector to prevent antiannealing of radiation damage be considered. While no fundamental obstacles for operating SVX II in Run II are foreseen, for Run III the inner layers may require yearly replacement after they have undergone type inversion from the accumulated dose, unless the device can be designed to withstand the substantial ($50 - 100\ V$) over voltages required to defeat the accumulation layer that may substantially increase the interstrip capacitance on the p-side, lowering the signal to noise ratio.

In this note I will compare several estimates of the amount of radiation damage that the SVX II detector will receive over Run II and into Run III of the TeVatron collider, a $2 f\mathrm{barn}^{-1}$ benchmark, and make several recommendations.

The future operation of the TeVatron is summarized in Table 1:

Table 1: Tentative TeVatron collider Run II and III luminosity.

Run	L cm^{-2} s^{-1})	$\mathcal{L}$ @ 10^7 s
IIa	2.0×10^{31}	$0.2 f\mathrm{barn}^{-1}$
IIb [a]	5.0×10^{31}	$0.5 f\mathrm{barn}^{-1}$
IIIa	1.0×10^{32}	$1.0 f\mathrm{barn}^{-1}$
IIIb	1.0×10^{32}	$1.0 f\mathrm{barn}^{-1}$

[a] With main injector upgrade operating at design L.

1 Layer 0 fluence

I will estimate the fluence received by SVX II sensors located in layer 0; first based on delivered luminosity and second on experience with the silicon tracker used in CDF for Run Ia, the SVX.

Estimate based on delivered luminosity

Assumptions:

- Strip length seen by p-side SVX II chip = 2 wafers $\times$ 8.5 cm; $l = 17.0$ cm
- Strip pitch; $p = 50$ μm
- Thickness of depletion layer; $t = 300$ μm
- $\mathcal{L} = \int L \, dt = 2 \, f\mathrm{barn}^{-1}$ (well into Run IIIb).

- $\frac{dN}{d\eta} = 4.2 \pm 0.19$ MIPs/event/unit pseudorapidity [1]
- 40 % of tracks curl multiply through the SVX II layers; $f_{\text{curl}} = 1.4$ [1]
- 40 % additional secondaries from inner layers and beam pipe; $f_{\text{secondary}} = 1.4$ [2]
- $\eta = -\ln\tan\left(\frac{\theta}{2}\right)$
- $\sigma_{\text{inelastic}} = 50.0 \pm 1.5$ mbarn [3]

From results obtained in reference [5] we calculate the number of charged particles per unit area Φ:

$$\begin{aligned}
\frac{dN}{dA} &= \frac{dN}{d\eta} \times \frac{d\eta}{dA} \quad \text{thus,} && (1)\\
\Phi_{\mathcal{L}} &= \frac{dN}{dA} \times \sigma_{\text{inelastic}} \times \mathcal{L} \times f_{\text{curl}} \times f_{\text{secondary}} \\
&= \frac{dN}{d\eta} \times \frac{\sin\theta}{2\pi r^2} \times \sigma_{\text{inelastic}} \times \mathcal{L} \times f_{\text{curl}} \times f_{\text{secondary}}, \quad \text{at } \theta = \frac{\pi}{2}\ \dagger : \\
&= 4.2 \text{ MIPs/event/unit pseudorapidity} \\
&\times \frac{1}{2\pi r^2} \times 50.0 \times 10^{-3}\text{ barn} \times 10^{-24}\text{ cm}^2\text{ barn}^{-1} \times 2 \times 10^{39}\text{ cm}^{-2} \times 1.4 \times 1.4 \\
&= \frac{1.31 \times 10^{14}\text{ MIPs}}{r^2} \quad \text{at } \theta = \frac{\pi}{2}\ (r \text{ in cm}) && (2)
\end{aligned}$$

† For wafers arranged in a barrel geometry, the path length through a thickness t of silicon for a stiff track will vary as $\frac{t}{\sin\theta}$. For sufficiently energetic particles this will approximately cancel the $\sin\theta$ dependence.

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[1] I assume that 40 % of the tracks curl through the detector, contributing to the total damage once on the outward traverse and once on the return [3]. Any r variation within SVX II ($r_0 = 2.416$ cm to $r_3 = 7.432$ cm) has been ignored.

[2] For layer 0, $f_{\text{secondary}}$ may vary depending on beam pipe composition. I will assume that the Be CDF beam pipe produces the same number of secondaries as a layer of silicon.

[3] In [2] $\sigma_{\text{total}} = 80.03 \pm 2.24\ mb$ and $\frac{\sigma_{\text{elastic}}}{\sigma_{\text{total}}} = 0.246 \pm 0.004$ at $\sqrt{s} = 1800\ GeV$. I am reducing $\sigma_{\text{inelastic}}$ from $60.34 \pm 1.69\ mb$ to $50.0 \pm 1.5\ mb$ to roughly account for singly and doubly diffractive $p\bar{p}$ collisions where one or both incident particles are scattered into the high η region and thereby do not contribute to the dose delivered to the detector.

Table 2: SVX detector parameters.

Layer	r (cm)	$\eta^{\dagger}$
0	2.99	±2.9
1	3.49	±2.5
2	5.28	±2.2
3	7.85	±1.9

† Referenced to the origin.

MODIFICATION OF RADIAL DEPENDENCE USING SVX EXPERIENCE

The SVX group [8] has measured the radial dependence of the *dose* within the fiducial volume of SVX, via analysis of regular calibration data including observed increases in amplifier noise, reduction in gain and increases in leakage currents with delivered luminosity. When the luminosity dependence and systematics are reduced by normalizing the data from other layers to layer 3, they find that the front-end chip noise varies radially as $\approx r^{-1.7}$. This includes several effects, including the variation of $\frac{dN}{d\eta}$ with η, which drops off above $\eta \approx 4$, and secondary interactions, where particles scattered from the inner layers or beam pipe may cause damage in subsequent layers. After consultation [9], I have chosen to follow the dependence associated with noise, which is attributable to the dose received by the front-end amplifier chips, which are located just beyond the SVX detector η [4], rather than the gain [5] or the dose as measured by the TLDs, which are located in the high η region, in the "10° hole" in the calorimeter. Thus, I will modify the functional form of Equation 2 to conform with their result:

$$\Phi_{\mathcal{L}}^{\rm SVX} = \frac{1.31 \times 10^{14}\,\rm MIPs}{r^{1.7}} \quad (r \text{ in cm}) \tag{3}$$

[4] The detector η of the SVX is given in Table 2.

[5] The gain is associated with these same front-end chips and convolved with the leakage current of the (DC coupled) sensors.

For layer 0, assume that $r_0 = 2.416$ cm ([10], Figure 45). This yields

$$\begin{aligned} \Phi_{\mathcal{L}}^{\rm SVX} &= 2.92 \times 10^{13}\ \text{MIPs/cm}^2 \text{ at } r_0 = 2.416\ \text{cm} \\ &= 0.78\ \text{MRad}^{6} \end{aligned} \qquad (4)$$

Estimate based on experience with SVX

The SVX group reported ([8], Figure 11 and [24], in a figure entitled "SVX dose vs Delivered Luminosity") a Layer 0 ($r_0 = 2.99$ cm) dose rate of approximately 0.35 kRad/$p$barn^{-1} for the majority of Run Ia, after the accelerator group had gained some experience with the SVX interlock and monitoring system. From this rate it is possible to extrapolate to the 2,000 $p$barn^{-1} benchmark.

$$\begin{aligned} \Phi_{\rm SVX} &= 3.5 \times 10^{-4}\ \text{MRad}/p\text{barn}^{-1} \times 2,000\ p\text{barn}^{-1} \\ &= 0.71\ \text{MRad} \\ &= 2.64 \times 10^{13}\ \text{MIPs/cm}^2 \text{ at } r_0 = 2.99\ \text{cm}. \end{aligned} \qquad (5)$$

For SVX II, we may scale this result by $(\frac{2.99}{2.416})^{1.7}$ to account for the difference between the layer 0 radii of SVX and SVX II to obtain

$$\begin{aligned} \Phi_{\rm SVX} &= 1.03\ \text{MRad} \\ &= 3.8 \times 10^{13}\ \text{MIPs/cm}^2 \text{ at } r_0 = 2.416\ \text{cm}. \end{aligned} \qquad (6)$$

This estimate is about 30 % higher than the value obtained in Equation 4 in Section 1. I will take Equation 6 as a more conservative, and realistic, estimate. The dose received by the other layers may be obtained by scaling by $r^{-1.7}$:

The fluence range necessary for type inversion using protons, $\Phi_{\rm invert} = 7.5 \times 10^{12}\ p^+/\text{cm}^2$ [12] to $\approx 1.05 \times 10^{13}\ p^+/\text{cm}^2$ (from [16], Figure 4. See also reference [15] for other values and a discussion of methodology). This variation in type inversion fluence is most probably due to differences in beneficial annealing of damage caused by temperature, beam intensity and beam energy variations between the various experiments. The damage

Table 3: SVX II dose *vs* r for $\mathcal{L} = 2.0\ f\mathrm{barn}^{-1}$.

Layer #	r (cm)	SVX II dose $p^+/\mathrm{cm}^2 \times 10^{13}$	MRad
0	2.416	3.8	1.03
1	3.491	2.0	0.54
2	5.282	1.0	0.27
3	7.432	0.6	0.16

produced by the pions predominating in minimum bias events is less (see Van Ginneken's calculation [4], plotted in Figure 1 of [5]) than protons by approximately a factor of two, and I choose the proton figure as a conservative upper estimate.

The fluences in Table 3 are based on an integrated luminosity of 2 $f\mathrm{barn}^{-1}$. From Table 1, this is well into the second year of Run III, at which point Layer 2 will reach type inversion. It should be repeated that this is a conservative estimate, based on the fluence required to invert the n-bulk silicon using protons, which are approximately twice as damaging as the pions which are the dominant species produced at the TeVatron interaction region.

2 Leakage currents

The ultimate bulk leakage current is given by [5]:

$$I_{\mathrm{leak}} = I_0 + \alpha \times \Phi \times V_{\mathrm{strip}} \quad (7)$$

where α, the damage coefficient, is dependent on the radiant particle species and the ambient temperature, I_0 is the bulk leakage current of the unirradiated device (negligible for the fluences under consideration in this paper) and the depletion volume of one strip, $V_{\mathrm{strip}} = l \times p \times t = 2.55 \times 10^{-3}\ \mathrm{cm}^3/\mathrm{strip}$. From [5], choose $\alpha = 3 \times\ 10^{-8}\ \frac{nA}{\mathrm{cm}}$ at $20^\circ\ C$. (Assume that α is known to about 30 %.) Thus, for the estimate based on anticipated delivered luminosity calculated in Equation 4,

$$
\begin{aligned}
I_{\text{leak}} &= 3\times10^{-8}\,\frac{nA}{\text{cm}}\times 2.92\times10^{13}\ \text{MIPs/cm}^2\times 2.55\times10^{-3}\text{cm}^3/\text{strip}\\
&= 2.23\ \mu A/\text{strip at } 20^\circ\ C
\end{aligned}
\tag{8}
$$

and for the estimate based on an extrapolation from experience with the operation of the SVX, from Equation 6,

$$
\begin{aligned}
I_{\text{leak}}^{\text{SVX extrap.}} &= 3\times10^{-8}\,\frac{nA}{\text{cm}}\times 3.8\times10^{13}\ \text{MIPs/cm}^2\times 2.55\times10^{-3}\text{cm}^3/\text{strip}\\
&= 2.91\ \mu A/\text{strip at } 20^\circ\ C
\end{aligned}
\tag{9}
$$

The leakage current value predicted from SVX experience is again 30 % higher than that calculated from the anticipated delivered luminosity. I will take this as a more conservative, and realistic, estimate.

The bulk I_{leak} may be corrected to other temperatures using [13]:

$$
I_{\text{leak}}(T_2) = I_{\text{leak}}(T_1)\left\{\frac{T_2}{T_1}\right\}^2 \exp\left\{\frac{-E}{2k}\left(\frac{T_1-T_2}{T_1T_2}\right)\right\}
\tag{10}
$$

Where T_1 and T_2 are absolute temperatures, k is the Boltzmann factor $8.617\times10^{-5}\ eV\ K^{-1}$ and $E = 1.2\ eV$ from a fit to data. At room temperature (300 K) this corresponds roughly to an increase in the leakage current by a factor of two for each 8.5° K rise in temperature.

The SVX group [6, 7] reports an increase in the bulk Layer 0 single strip leakage current of 30 nA over Run Ia or approximately 2 μ A/MRad/strip at the SVX operating temperature of 22° C. This figure was obtained from calibration data taken during "quiet time" while there were no beams in the TeVatron. The DC coupling of the SVXD front-end chips to the strips in the SVX sensors was exploited by collecting leakage charge for several time intervals giving a measure of the leakage current. There may be some questions about the leakage calibration, the normalization and other systematic errors; no uncertainty is reported. This technique will not be possible in SVX′ or SVX II which are AC coupled detectors.

Scaling by $(\frac{2.99}{2.416})^{1.7}$ to convert, approximately, to SVX II's Layer 0, we predict a total leakage current of 3.5 μA/MRad/strip or 1.17 $\mu A/10^{13}\ p^+/\mathrm{cm}^2$/strip. For $\mathcal{L} = 2\ f\mathrm{barn}^{-1}$ we expect

$$\begin{aligned} I_{\mathrm{leak}}^{\mathrm{SVX\ meas}} &= 1.17\ \mu A/10^{13}\ p^+/\mathrm{cm}^2/\mathrm{strip} \times\ 3.8\ \times\ 10^{13}\ \mathrm{MIPs/cm}^3 \\ &= 4.5 \mu A/\mathrm{strip\ at\ } 22^\circ\ C \end{aligned} \qquad (11)$$

The enormity of this figure should not pass without comment, this speaks of disastrous consequences for a variety of reasons. Assuming a 100 V applied bias, each ***strip*** would draw 450 μW which is a significant amount of heat for the gas to dissipate. It raises the prospect of thermal runaway (see equation 10). These are strong arguments to cool the detector.

The severity of the increase in leakage current with luminosity may prove to be a limiting factor: the inner layers of SVX II may require replacement *before* type inversion is reached due to the excessive leakage currents.

The 3.5 μA/MRad/strip figure does not include the contribution due to surface effects. Since the surface component is sensitive to gluing, handling and other mechanical influences a construction protocol to minimize the contribution of these effects to the surface leakage current should be implemented.

NOISE

For AC-coupled detectors such as SVX II the leakage current will not saturate the front-end chip input stage. However, the shot noise equivalent in electrons Q_{shot}, seen by the front-end chip may be obtained from [11].

$$I_{\mathrm{shot}}^{\mathrm{rms}} = \sqrt{2\ q_e\ I_{\mathrm{leak}}\ B} \qquad (12)$$

where q_e is the electronic charge and B is the bandwidth of the front-end chip.

Spieler, [18] has calculated the squared equivalent noise charge

$$Q_{\mathrm{shot}}^2 = 2 q_e I_{\mathrm{leak}} F_i \tau \qquad (13)$$

for a CR-RC shaper with time constants $RC = CR = \tau_{\rm integrate} = \tau_{\rm differentiate} \equiv \tau$ and $F_i = 0.924 \approx 1$ [7]. The equivalent shot noise count in terms of electrons is given by

$$Q_{\rm shot}/q_e = \sqrt{2 \times \frac{I_{\rm leak}\ t_{\rm int}}{q_e}} \tag{14}$$

where $t_{\rm int}$ is typically 100 ns or less. Taking $t_{\rm int} = 100\ ns$, for the SVX extrapolation we obtain:

$$\begin{aligned} Q^{\rm SVX}_{\rm shot} &= \sqrt{2 \times \frac{2.91\ \mu A \times 100\ ns}{1.602 \times 10^{-19}\ \text{coulombs}/e^-}} \\ &= 1,904\ e^- \end{aligned} \tag{15}$$

Table 4: Rad soft SVX II front end chip measured input noise

$C_{\rm input}$ (pF)	$\tau_{\rm rise}$ (ns; 10 % to 90 %)	$Q_{\rm input}$ (e^-)
20	104	1,070 [20]
33	42	2,320 [21]

The measured equivalent input noise due to electronic noise and detector capacitance for the radiation soft version of the SVX II chip is shown in Table 4. For the radiation hard version we expect somewhat higher values. Thus, I have chosen an unrealistically high 33 pF value for the input capacitance to compensate for the lack of data for a rad hard chip.

The Johnson (thermal) noise of a resistance R at absolute temperature T over bandwidth B is given by

$$V_{\rm Johnson} = \sqrt{4kTRB} \tag{16}$$

where $k = 1.381 \times 10^{-23}\ J\ K^{-1}$. For SVX II, assume 2 M Ω bias resistors and that $B = t_{\rm int}^{-1}$,

[7] For a detailed treatment of noise issues see [19].

$$
\begin{aligned}
V_{\text{Johnson}} &= \sqrt{\frac{4kTR}{t_{\text{int}}}} \\
&= \sqrt{\frac{4 \times 1.381 \times 10^{-23}\ J\ K^{-1} \times 293^{\circ}\ K \times 2 \times 10^{6}\ \Omega}{100 \times 10^{-9} s}} \\
&= 5.69 \times 10^{-4}\ V
\end{aligned} \tag{17}
$$

The Johnson voltage may be converted to an equivalent noise charge in coulombs by multiplying by the effective capacitance:

$$
Q_{\text{Johnson}} = C_{\text{eff}}\ V_{\text{Johnson}} \tag{18}
$$

where $C_{\text{eff}} = t_{\text{int}}/R$. Thus,

$$
Q_{\text{Johnson}} = \sqrt{\frac{4kTt_{\text{int}}}{R}} \tag{19}
$$

and, in terms of electrons,

$$
\begin{aligned}
Q_{\text{Johnson}} &= \sqrt{\frac{4 \times 1.381 \times 10^{-23}\ 93^{\circ}\ K \times 100 \times 10^{-9} s}{2 \times 10^{6}\ \Omega\ (-1.602 \times 10^{-19} \text{coul}/e^{-})^2}} \\
&= 178\ e^{-}
\end{aligned} \tag{20}
$$

Q_{Johnson}, Q_{shot} and Q_{input}, add in quadrature. I will use the larger value of Q_{input} quoted above. While the input capacitance to ground, 33 pF, is relatively large, this is also based on a measurement using a rad-soft chip. My choice of this value represents a compromise between these offsetting effects:

$$
\begin{aligned}
Q_{\text{noise}} &= \sqrt{Q^2_{\text{Johnson}} + Q^2_{\text{shot}} + Q^2_{\text{input}}} \\
&= \sqrt{(178\ e^{-})^2\ +\ (1,905\ e^{-})^2\ +\ (2,320\ e^{-})^2} \\
&= 3,007\ e^{-}
\end{aligned} \tag{21}
$$

For a 300 μm thickness detector, assuming 100 % collection by the front-end chip and a minimum ionizing particle producing 80 $e - hole$ pairs μm^{-1} for a signal of 24,000 electrons, the signal to noise ratio is:

$$S/N = 24,000\ e^-/3,007\ e^- = 8 \tag{22}$$

3 Depletion Voltages

From reference [12], Figure 2 and reference [17], Figure 10, for Run II, the depletion voltage will remain well below 30 V. Assuming 50 V over depletion to assure prompt charge collection and to reduce the p-side interstrip capacitance [8] there still should be no problems associated with "popcorn" noise [23] on the p-side [9] or breakdown with the detector maintained at 20° C. If Run II is extended, or if the SVX II detector is used in Run III or CDF-B is posited, then this scenario should be reevaluated and the possibility of replacing the inner layer or maintaining the silicon at 0° C, to allow beneficial annealing of the bulk damage and defer harmful antiannealing (see [17]) should be considered. A study of neutron backgrounds similar to that of Palounek [25] should also be considered.

4 Interstrip Capacitance

The UCSC group [22, 26] has measured the change in the AC and DC interstrip capacitance as a function of dose for Hamamatsu n-bulk silicon AC-coupled single-sided detectors manufactured with either junction (p-side) or ohmic (n-side) processing to simulate both sides of a double-sided device. These detectors were intended as prototypes for the SDC silicon tracker. They have both their n- and p-side strips arranged at a 50 μm pitch at four

[8] In [22] over voltages of 100 V beyond depletion are reported to be required to reduce the interstrip capacitance on the p-side for detectors that have received 5 MRrad of γ and 3.5 MRrad of p^+ (sufficient exposure to invert the bulk silicon) down to approximately 20 % over their pre-irradiation value.

[9] The p-side was shown to be more susceptible to "popcorn" noise (micro discharges of the coupling capacitors) as a function of V_{bias}; $V^n_{pop} \approx V^p_{pop} + 30\ V$, where $V^p_{pop} \approx 65\ V$. See [23].

sample widths. The UCSC group accumulated a total of $\dot{\Phi} = 3.5$ MRad of proton irradiation in their study.

For the p-side, (diode side) they note that the interstrip capacitance [10] increases with fluence, to approximately 120 % of the unirradiated value after 100 - 200 kRad of proton irradiation. At about 500 kRad the n-bulk inverts and the interstrip capacitance is 200 % of the initial value. (With proton irradiation the now p-bulk silicon depletes from the n-side.) Beyond type inversion, the interstrip capacitance may be reduced to approximately 150 % of the pre-irradiation value by application of an over voltage field (≈ 50 to $100\ V$ above depletion), indicating the presence of bound charges near the surface (an "accumulation layer").

For the n-side (ohmic side) which contained 24 μm width p^+-doped blocking implants to isolate the 12 μm n^+-doped DC strips [11] the interstrip capacitance increases to about 120 % of the pre-irradiation value after approximately 200 kRad. Following type inversion, the n-side interstrip capacitance *decreases* to a value similar to that of the pre-irradiation p-side, around 1 pF/cm [27].

Since the inner layers of SVX II will invert before Run II is concluded, it is advisable to choose a design that can tolerate the highest bias ($V_{\mathrm{depletion}}$ + over voltage) voltages possible and that has minimal interstrip capacitance. Consideration should be given to the possibility of replacement of the inverted layers should this not be possible.

5 Conclusion

The experience gained from the operation of the SVX in Run Ia (and that we will gain from the SVX′ in Run Ib) provides the best indicator of what we may expect for SVX II in Run II. The dose monitoring and interlocks [8, 24] curbed accidental doses and provided valuable information to the TeVatron's accelerator control which lead to an optimum scraping procedure. These practices should be continued with SVX II and Run II. As in Run Ia every

[10]The coupling capacitance was found to be stable over the range of fluences tested, and the bulk effects are detailed in [17].

[11]For a double-sided detector, the accumulation layer may short the n-side strips unless blocked by an intervening p^+ implant.

possible effort should be made to eliminate or reduce non-luminosity driven sources of radiation damage.

The Run II dose is expected to result in depletion voltages below $50V$; below breakdown and the onset of frequent "popcorn" noise. If this detector is to be used in Run III or a B detector in the B0 collision hall, consideration should be paid to the possibilities of maintaining the detector at $0° C$ on a permanent basis and the replacement of the inner layers, with the attendant engineering considerations.

We should count on Layers 0 and 1 undergoing type inversion. In this regime an overvoltage of at least 50 volts over depletion will be required to promptly read-out the device and overcome the effects of the accumulation layer that increases the interstrip coupling capacitance on the p-side.

The factor of two increase in p-side coupling capacitance with dose as reported by the UCSC group is a concern for the contribution to noise. Further investigations are warranted to determine whether any effect will occur for the double-metal layer under irradiation.

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