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Effects of Radiation Damage on the DØ Silicon Tracker

John Ellison and Ann Heinson
UC Riverside

Abstract

This note presents calculations of full depletion voltages, leakage currents and shot noise in the DØ Silicon Tracker, as functions of silicon temperature and delivered integrated luminosity. The charged particle and neutron fluence calculations are based on DØ note 1155 [1] as are the shot noise calculations. However, parameters used in that note which are now different or are better known include the Tevatron operating energy, the height of the pseudorapidity plateau for minimum bias events, the addition of the solenoid in DØ for Run II and the CDF measurements of doses in Run Ia.

We also present predictions of the change in full depletion voltage as a function of the integrated luminosity. These predictions are based on recent studies of the radiation induced change in depletion voltage which have resulted in a better understanding of detector annealing and antiannealing effects.

1. Radiation Dose

The proton–antiproton inelastic cross section at $\sqrt{s} = 1.8$ TeV is 60.0 mb [2]. However, at $\sqrt{s} = 2.0$ the estimated inelastic cross section is 61.5 mb. This raises the charged particle fluence slightly compared with the calculation in DØ note 1155. Another factor not included in calculations in DØ note 1155 is the 2 T field, which was not present for the former "Step 1" tracker. Low momentum particles will loop around and pass through the Silicon Tracker more than once. We have allowed a factor of two for this, based on GEANT studies. Therefore, the number of charged particles per unit area will be:

$$\phi_{ch} = \frac{2H\sigma_{\text{inelastic}}}{2\pi r_{\perp}^2} = \frac{9.79\times 10^{10}}{r_{\perp}^2} \quad [\text{cm}^{-2}/\text{pb}^{-1}]$$

where H is the height of the pseudorapidity plateau at 2 TeV and $r_{\perp}$ is the perpendicular distance of the silicon detector from the beam line. We use $H = 5.0$, based on reference [3] in the region $|\eta| < 2.5$ compared with $H = 4.0$ used in DØ note 1155. The DØ Silicon Tracker inner barrel layer is at 2.78 cm radius from the beam line.

The number of neutrons per unit area for Run II is taken from DØ 1155, scaled here for the slightly higher value of H:

$$\phi_n = 1.5\times 10^9 \quad [\text{cm}^{-2}/\text{pb}^{-1}]$$

The total fluence of particles through the silicon is higher than just the sum of the calculated charged and neutron fluences from steady running. Extra factors include beam loss through the tracker during Tevatron startup and beam tuning losses at the start of each injection and run.

The CDF SVX group has estimated [4] the dose to their detector for Run Ia as a function of delivered luminosity. The measurements made were of charged dose only. The dose was found to be ~ 4000 rads + 350 rads/pb^{-1} at 2.99 cm radius. The 4 krad term comes from catastrophic beam losses through the SVX detector during the first ten weeks of Tevatron startup. The second term is the dose received during steady Tevatron running after the first ten week period. Since 1 rad ≈ 3.8×10^7 mip/cm^2, this gives for the steady running period, ϕ_{ch}(CDF) = (1.19×10^{11} / $r_{\perp}^2$) cm^{-2}/pb^{-1}. This is a factor of approximately 1.2 higher than the calculation above. The extra dose received by the SVX was probably due to beam loss during tuning [1,5].

In our calculations we include the factor 1.2 but we ignore the 4 krad term due to run startup, as this is small compared with the total fluences expected in Run II. Figure 1 shows the charged particle and neutron fluences as a function of radius for an integrated luminosity of 1 pb^{-1}.

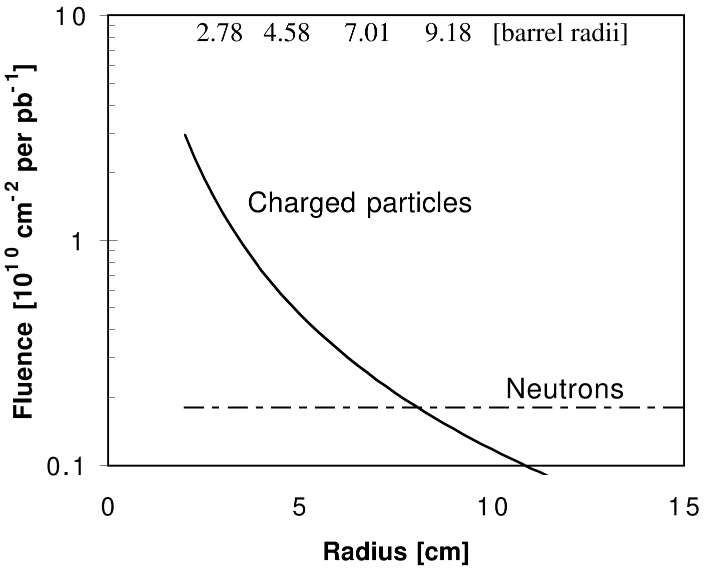


Fig. 1. Charged particle and neutron fluences for 1 pb^{-1} as a function of radius.

2. Bulk Doping Concentration Effects

Recently, knowledge of the effects of radiation damage has improved significantly, as presented in a paper by Ziock et al. [6] from studies for the SDC Silicon Tracker. Type inversion, where the n-type bulk silicon becomes effectively p-type, occurs after ~ 1×10^{13} protons/cm^2, although if there is neutron radiation as well, inversion will occur earlier. As a silicon detector is bombarded with particles, donor removal and acceptor creation occur and the effective doping concentration of the bulk silicon slowly changes. This affects the voltage needed to fully deplete the detectors for efficient operation. The depletion voltage V_D is given by :

$$V_D \approx \frac{q d_D^2 \left| N_{eff} \right|}{2\varepsilon_s}$$

where

q is the electronic charge

d_D = 300 μm is the detector full depletion depth

N_{eff} is the effective bulk doping concentration

$\varepsilon_s = 11.9 \times 8.854$ pF/cm is the relative permittivity of silicon.

Annealing effects result in a time dependent change in N_{eff} and therefore in the full depletion voltage. This has been parametrized in Ref. [6]. The long term increase in depletion voltage as a function of time t, including the effects of short term annealing and long term antiannealing, is given by [6],

$$V_D(t) = Ft\left\{\nu_Z + \nu_S \frac{\tau_S}{t}\left[1-\exp(-t/\tau_S)\right] + \nu_A\left\{1+\frac{\tau_L}{t}\left[-1+\exp(-t/\tau_L)\right]\right\}\right\}$$

The parameters ν_Z, ν_S and ν_A are independent of the temperature and scale with the detector thickness squared. For $d = 300$ μm,

$\nu_Z = 1.06 \times 10^{-12}$ Vcm^2	describes the fraction of the radiation produced acceptor concentration which is stable,
$\nu_S = 1.34 \times 10^{-12}$ Vcm^2	describes the metastable acceptor concentration directly produced during the irradiation process,
$\nu_A = 3.80 \times 10^{-12}$ Vcm^2	describes the concentration of damage sites in silicon that can become activated acceptor sites due to antiannealing.

τ_S and τ_L are the short-term and long-term annealing time constants respectively and are exponential functions of the detector temperature:

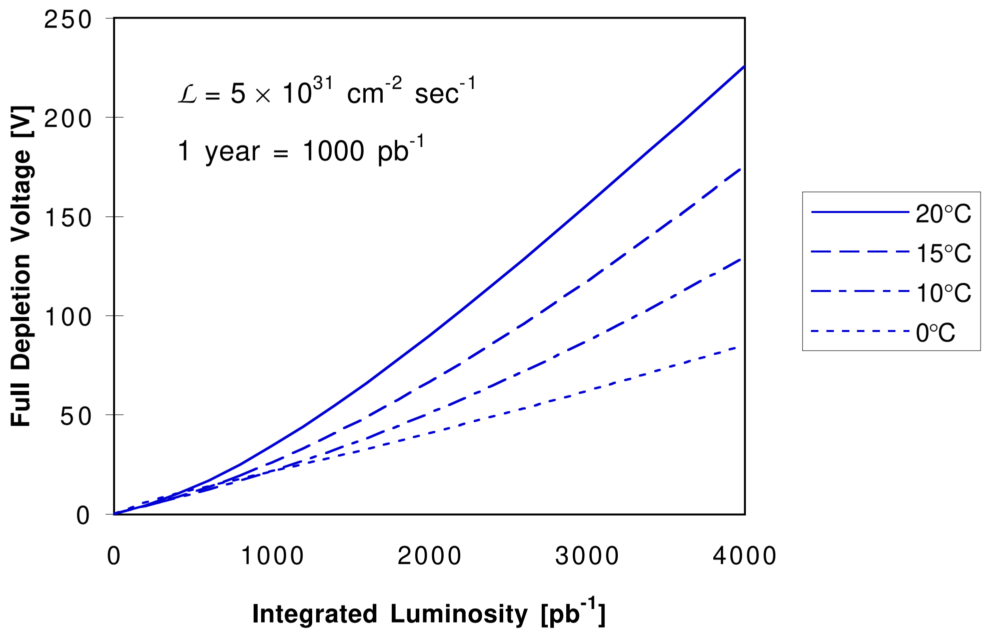
$$\tau_S(T) = 70\exp(-0.175T) \quad \text{[days]}$$
$$\tau_L(T) = 9140\exp(-0.152T) \quad \text{[days]}$$

where the temperature T is in units of °C.

The fluence dependence in the above equation is contained in the term F, which is the particle flux (fluence per second), and is assumed to be constant. The average flux depends on the Tevatron luminosity and the fraction of the time during the run that the Tevatron is running. We assume this fraction to be two thirds.

The above parametrization was made using 800 MeV proton damage data. Pions, which are the major component of the charged particle fluence at the Tevatron, have a smaller nonionizing energy loss in silicon (by a factor of about 2) and therefore are expected to produce less damage. However, we use the proton parametrization given above to obtain a conservative estimate of the radiation damage. We ignore the neutron damage since at the inner radius of the tracker ($r_\perp = 2.78$ cm), the charged particle fluence completely dominates, as shown in Fig. 1.

Figure 2 shows the predicted full depletion voltage of the inner barrel detectors as a function of integrated luminosity for different values of the silicon temperature, at (a) $\mathcal{L} = 5 \times 10^{31}$ cm^{-2}s^{-1}, (b) $\mathcal{L} = 1.0 \times 10^{32}$ cm^{-2}s^{-1}, (c) $\mathcal{L} = 2.0 \times 10^{32}$ cm^{-2}s^{-1}, and at (d) $\mathcal{L} = 1.0 \times 10^{33}$ cm^{-2}s^{-1}. The total integrated luminosity delivered in one year is indicated on each plot.



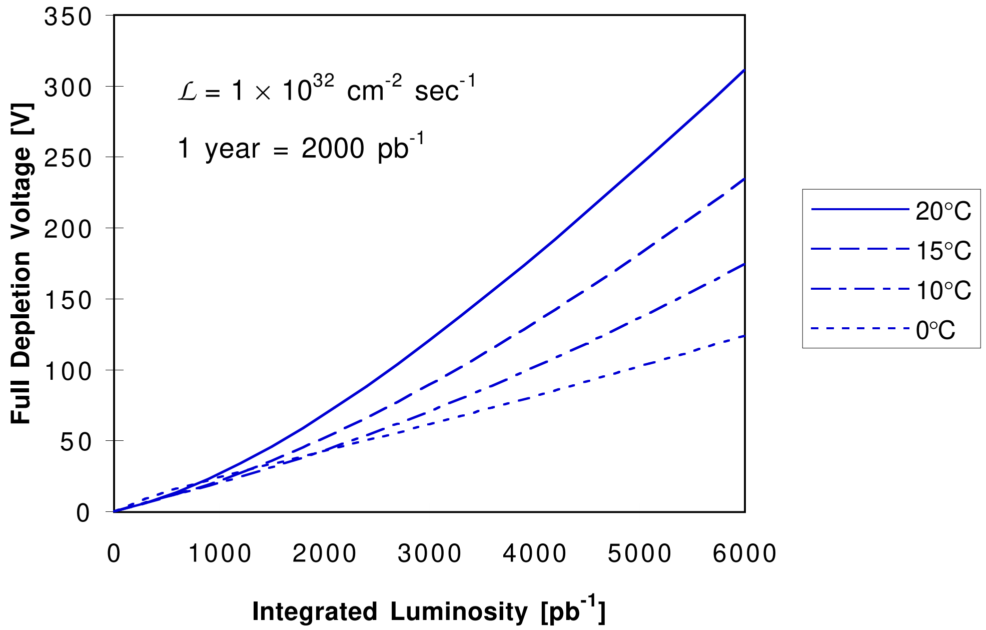


Fig. 2a,b Full depletion voltage for the barrel inner layer at r = 2.78 cm, as a function of integrated luminosity for $\mathcal{L} = 5 \times 10^{31}$ cm^{-2} sec^{-1} and $\mathcal{L} = 1 \times 10^{32}$ cm^{-2} sec^{-1}.

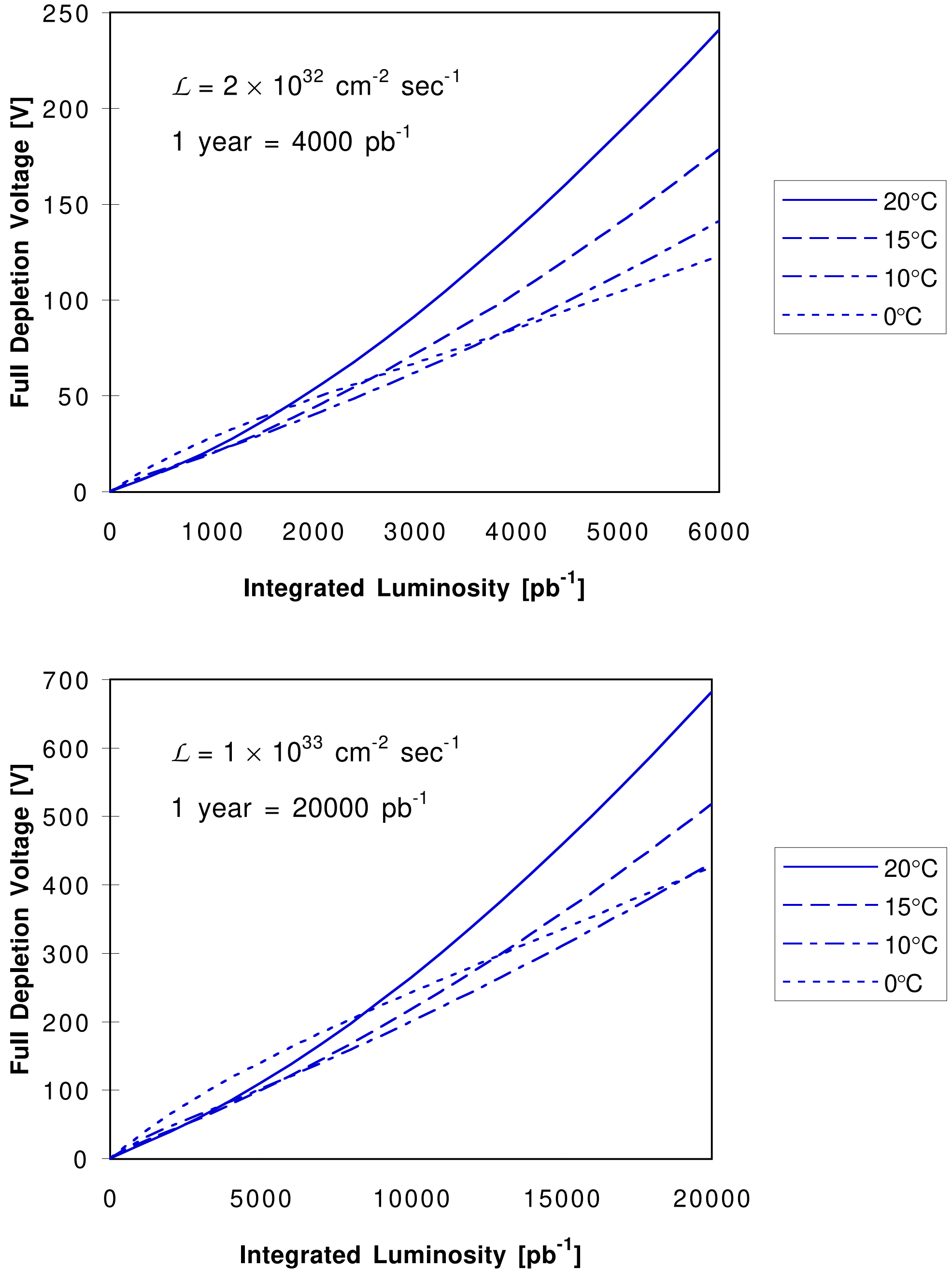


Fig. 2c,d Full depletion voltage for the barrel inner layer at r = 2.78 cm, as a function of integrated luminosity for $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} sec^{-1} and $\mathcal{L} = 1 \times 10^{33}$ cm^{-2} sec^{-1}.

Assuming that the maximum full depletion voltage for practical operation is about 100 V, we see by inspection of Fig. 2 that the lifetime of the detectors in the inner barrel will be approximately 2.5 fb^{-1} at 20°C, 3.5 fb^{-1} at 15°C and 4 fb^{-1} at 10°C.

3. Leakage Current Effects

The total leakage current in a single strip is given by [1]:

$$I = I_0 + V(\alpha_{ch}\phi_{ch} + \alpha_n\phi_n) \approx V(\alpha_{ch}\phi_{ch} + \alpha_n\phi_n)$$

where I_0 is the initial leakage current, V is the detector element volume, α_{ch} , α_n are the charged particle and neutron damage constants and ϕ_{ch} , ϕ_n are the charged particle and neutron fluences. For the barrel detectors the strip length is 11.7 cm, the thickness is 300 μm and the strip pitch is 50 μm. We use $\phi_{ch} = \phi_n = 3 \times 10^{-17}$ A cm^{-1} for the damage constants. The temperature dependence of the leakage current is given by [7]

$$I \propto T^2 \exp\left(\frac{-E}{2kT}\right)$$

where $E \approx 1.2$ eV and k = 8.6 × 10^{-5} eV/K is Boltzmann's constant. The constribution of the leakage current to the SVX II shot noise is approximated by the expression for an RC-CR shaping amplifier:

$$ENC\,(\text{r.m.s.electrons}) = \frac{e}{2}\sqrt{\frac{\tau I}{q}}$$

where e = 2.7183, q is the electron charge, τ is the shaping time (i.e. the SVX II sampling time), and I is the leakage current.

Figure 3 shows the shot noise due to radiation induced leakage current in the inner barrel layer (r = 2.78 cm) as a function of integrated luminosity, where we have assumed an SVX II sampling time of 132 ns , corresponding to operation of the Tevatron at 132 ns bunch crossing time.

The intrinsic noise of the SVX II chip is set by the detector capacitance. At 132 ns operation the noise is parametrized as[1]

$$ENC\,(\text{r.m.s.electrons}) = 450 + 65\,C_D$$

[1] This parametrization is based on measurements made on prototype SVX II's with a sampling time of 150 ns. Measurements were also made with τ = 400 ns and are parametrized in the equation on page 8. The measurement data were ontained form R. Yarema and T. Zimmerman

where C_D is the detector strip capacitance in pF. For the barrel detectors the p-side capacitance is 14.5 pF [8]. This gives an intrinsic SVX II noise of 1400 e^-. If we require that the signal-to-noise ratio remains above 10:1 this means that the maximum allowed shot noise contribution is 1950 e^-. This results in an inner barrel detector lifetime of 5.5 fb^{-1} at 20°C, 8.7 fb^{-1} at 15°C, 13.7 fb^{-1} at 10°C and >20 fb^{-1} at 0°C.

If the SVX II is operated with a sampling time of 396 ns, the noise can be parametrized as

$$ENC\,(\text{r.m.s. electrons}) = 283 + 49\,C_D$$

and the radiation induced shot noise will be a factor of $\sqrt{3}$ higher than shown in Fig. 3. Using the same criterion that the signal-to-noise ratio remain above 10:1 results in shorter detector lifetimes. The results are summarized in Table 1.

It is interesting to note that to obtain the lowest noise in the inner barrel layer, it is better to run with the shorter SVX II sampling time (τ = 132 ns), even if the Tevatron is operating with a 396 ns bunch crossing time. This is true only after sufficient radiation exposure (>1 fb^{-1} at 15°C and >5 fb^{-1} at 0°C). The noise improvement is considerable for moderate operating temperatures, and is reduced at lower temperatures. These effects are shown in Fig. 4, which shows the *total* noise as a function of integrated luminosity for short and long sampling times and operation at 15°C and 0°C.

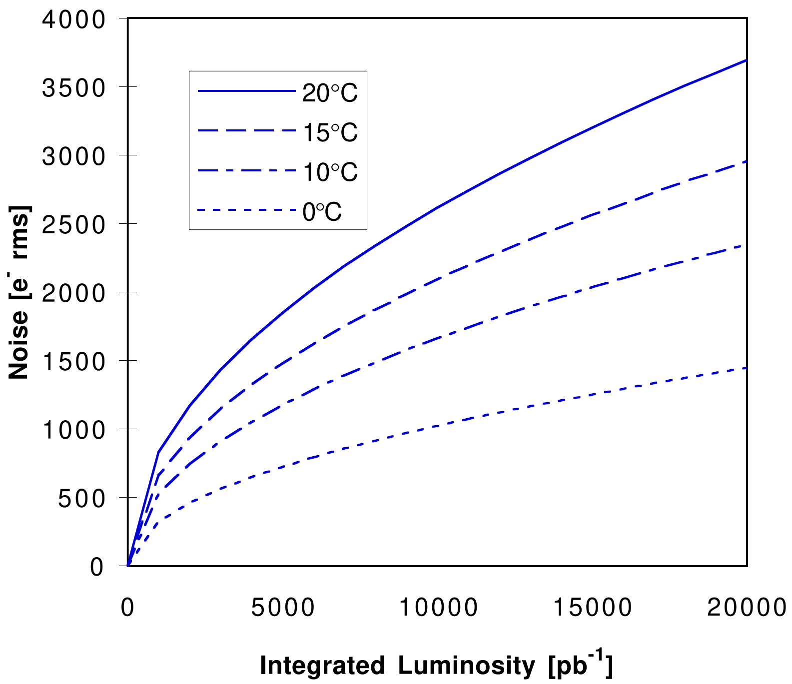


Fig. 3. Shot noise due to the radiation induced leakage current in the inner barrel layer as a function of integrated luminosity for τ = 132 ns.

	Lifetime (fb^{-1})	
Temperature (°C)	τ = 132 ns	τ = 396 ns
20	5.5	2.3
15	8.7	3.6
10	13.7	5.6
0	>20	14.8

Table 1. Detector lifetimes due to radiation induced leakage current shot noise for different silicon detector temperatures and SVX II sampling times.

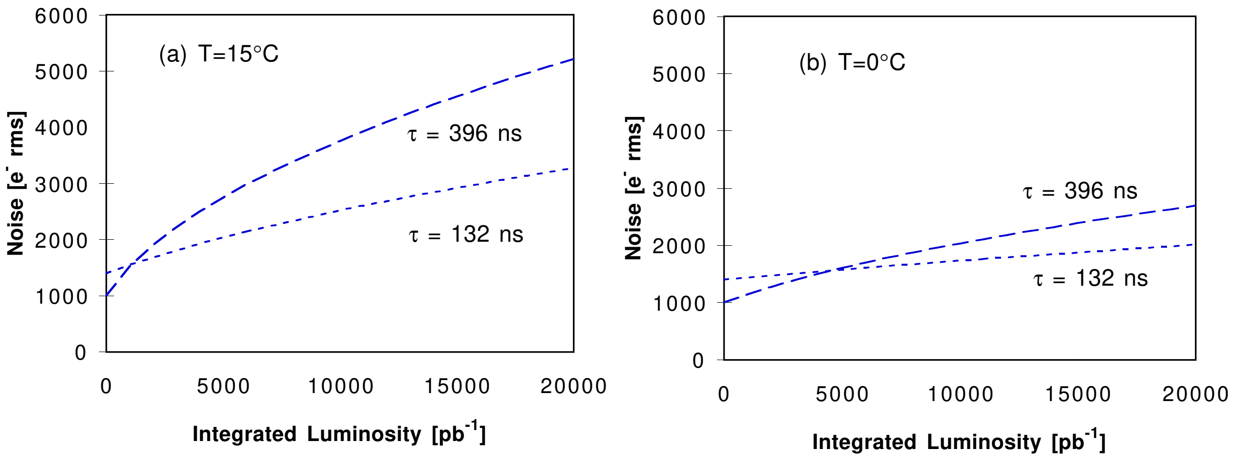


Fig. 4. Total noise in the inner barrel layer as a function of integrated luminosity for (a) T=15°C and (b) T=0°C. For a signal-to-noise ratio of 10:1 the total noise must remain below 2,400 e^- r.m.s.

4. Conclusions

The charged particle and neutron fluences in the tracking volume of the upgraded DØ detector have been calculated, giving

charged particles: $$\phi_{ch} = 1.2 \times \frac{9.79 \times 10^{10}}{r_\perp^2} = \frac{1.175 \times 10^{11}}{r_\perp^2} \quad [\mathrm{cm}^{-2} / \mathrm{pb}^{-1}]$$

neutrons: $$\phi_n = 1.2 \times 1.5 \times 10^9 = 1.8 \times 10^9 \quad [\mathrm{cm}^{-2} / \mathrm{pb}^{-1}]$$

The effects of radiation on the detector leakage current and full depletion voltage have been estimated as functions of the instantaneous luminosity, the integrated luminosity and the silicon microstrip detector operating temperature.

If we require that the signal-to-noise ratio remain above 10:1, the radiation induced shot noise for an SVX II sampling time of 132 ns limits the detector lifetime to 5.5 fb^{-1} at 20˚C, 8.7 fb^{-1} at 15˚C, 13.7 fb^{-1} at 10˚C and >20 fb^{-1} at 0˚C. For high integrated luminosities, lower noise in the *inner* layer is achieved by running with the short SVX II sampling time (τ = 132 ns), even if the Tevatron is operating with a 396 ns bunch crossing time (see Fig. 4).

The detector lifetime, resulting from changes in the effective doping concentration, assuming that the maximum full depletion voltage for practical operation is 100 V, is approximately 2.5 fb^{-1} at 20˚C, 3.5 fb^{-1} at 15˚C and 4 fb^{-1} at 10˚C.

References

[1] J.A. Ellison, "Radiation Levels in DØ and Effects on Silicon Detectors", DØ 1155, (July 1991).

[2] F. Abe *et al.*, "Measurement of the Antiproton-Proton Total Cross Section at $\sqrt{s}$ = 546 and 1800 GeV", Phys. Rev. D **50**, 5550 (1994).

[3] F. Abe *et al.*, "Pseudorapidity Distributions of Charged Particles produced in $\bar{p}p$ interactions at $\sqrt{s}$ = 630 and 1800 GeV", Phys. Rev. D **41**, 2330 (1990).

[4] D. Amidei *et al.*, "Status of Radiation Damage to the SVX", CDF/SVX/DOC/PUBLIC/2061, (April 1993).

[5] S. Vejcik (CDF SVX group), private communication.

[6] H.-J. Ziock, J.A. Ellison, A.P. Heinson *et al.*, "Temperature Dependence of the Radiation Induced Change of Depletion Voltage in Silicon PIN Detectors", Nucl. Instrum. Methods **A342** (1993) 96.

[7] E. Barberis, J.A. Ellison, *et al.*, "Temperature Effects on Radiation Damage to Silicon Detectors", Nucl. Instr. Meth. **A326** (1993) 373.

[8] DØ Silicon Tracker Technical Review, DØ note 2400, 11/12/94. See the transparencies from J. Ellison's talk.