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Signal Simulations for Double-sided Silicon Strip Detectors

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Abstract

Signals resulting from the passage of minimum ionizing charged particles through the double-sided silicon strip detector of the SDC experiment for the SSC are simulated, including the effects of Landau fluctuations and the drift of electrons and holes in the electric and magnetic fields inside the detector. These calculations are done for both the p-side of the detector, which collects holes on p implants, and the n-side, which collects electrons on n implants. Induced currents are integrated, shaped and discriminated after addition of random electrical noise, and the timing of signals is obtained. Using the results of many Monte Carlo generated events, efficiencies, position resolutions, and means are evaluated as functions of the threshold, the signal-to-noise ratio, the amplifier shaping time, and the data storage time-window. The n-side of the detector has a more prompt signal and is less sensitive to the signal-to-noise ratios and detector voltage. This compensates for the somewhat larger electronic noise expected on the n-side due to a higher detector capacitance than on the p-side. Irradiation of the detector does not change these results very significantly provided the detector bias voltage is suitably adjusted.

I. Introduction

The use of an array of silicon strip devices in a magnetic volume is an attractive choice for a charged particle detector which aims to optimize pattern recognition and overall tracking performance at the SSC. The stringent requirements on timing accuracy, data storage, radiation resistance, and allowable material in the tracking volume make the electronics readout of such detectors a challenging problem. To help in the design of the front-end electronics we have developed a computer program which simulates the performance of the combined detector and front-end system. Included are the effects of an external magnetic field and fluctuations in energy deposited by particles traversing the detector, as well as the electrical and timing characteristics of the detector and its readout electronics [1].

II. Description of Detector

The layout under consideration for the SDC detector at the SSC contains silicon detectors in both a barrel configuration, forming cylindrical layers surrounding the beampipe, and planar annular disks covering the forward and backward directions. In this paper we will consider the barrel detectors only. These detectors have an active area of about 6 cm by 3.2 cm and are bonded together in pairs to form 12 cm long readout units. The detector units are double-sided, with strips on one side running parallel to the 12 cm long detector edge, and on the other side providing small angle stereo measurements via strips tilted by 10 milliradians. The configuration of detection elements, as well as the electrode characteristics of an individual detector can be found in Ref. [2]. The pitch for charge collection and readout is 50 μm on both sides of the detector. The charge collecting implants are expected to be about 10 μm wide on both sides of the detector and isolation between the n-implants is provided by p-blocking strips which fill most of the gap between these collection electrodes.

To calculate the induced current on any strip, three things are needed: 1) The electromagnetic fields in the detector, 2) The energy (or, equivalently, the number of electron/hole pairs) deposited along the traversing particle's track, and 3) the weighting field (defined below). In our simulations, the B-field is fixed at $\vec{\mathrm{B}} = (2\mathrm{Tesla})\hat{\mathrm{z}}$. (See Fig. 1 for the definition of our coordinate system.) The electric field, $\vec{E} = -\vec{\bigtriangledown} V$, is determined by solving Poisson's equation, $\bigtriangledown^2 V = -\rho/(\varepsilon_o \varepsilon_{Si})$, on a discrete mesh in x and y. Typical mesh sizes are $dx = 1\mu$m, $dy = 1\mu$m near the strips (within one pitch), and $dy = 10\mu$m elsewhere, and the charge density ρ (assumed to be uniform) is given by the acceptor and/or donor concentrations in the bulk silicon. The boundary conditions are: 1) $V = 0$ at the p-strips, 2) $V = V_{\mathrm{bias}}$ at the n-strips, 3) $dV/dy = 0$ in the interstrip region and 4) periodic boundary conditions, with period=pitch, at the sides of the detector, which in our simulations occur at $x = \pm 6{\cdot}$pitch. We subsequently refer to $V_{\mathrm{depletion}} = \frac{e\ depth^2 |\rho|}{2\varepsilon_o \varepsilon_{Si}}$ instead of ρ. Given $V_{\mathrm{bias}} = V_{\mathrm{depletion}}$, the detector is (just barely) fully depleted, with the electric field vanishing at the n-strips (for n-type silicon). Generally we run in the *over-depleted* mode ($V_{\mathrm{bias}} > V_{\mathrm{depletion}}$) with $E_y > 0$ everywhere, allowing for faster charge collection times.

Knowing the fields, we can calculate the drift velocity using a parameterization by Muller and Kamins [3] which includes the the saturation of $|\vec{v}|$ at high fields and the dependence of $\vec{v}$ on temperature which we hold at 273°K:

$$\vec{v} = v_l \frac{\vec{F}}{F_c} [\frac{1}{1 + (|\vec{F}|/F_c)^\beta}]^{1/\beta},$$

where $\vec{F} = \vec{E} - \mu^H_{e,h} \vec{E} \times \vec{B}$. The values used for the Hall mobilities μ^H [4,5] and for the temperature dependent parameters v_l, F_c, and β, with $T = 273$°K, are given in Table 1. Notice that $\frac{(v_l/F_c)_{electrons}}{(v_l/F_c)_{holes}} = 3.2$, causing the electrons to be collected approximately three times faster than the holes.

Table 1. Drift Velocity Parameters

Parameter	Electrons	Holes
μ^H $[\mu m^2/(V\ ns)]$	135.	31.
v_l [μm/ns]	116.	88.
F_c [V/μm]	0.6	1.5
β	1.04	1.19

Ignoring saturation effects $\vec{v}_{e,h}$ is proportional to $\pm(\vec{E} \mp \mu^H_{e,h}\vec{E} \times \vec{B})$ so, with $E_x \approx 0$ in much of the detector, $v_x/v_y \approx \mu^H_{e,h}B$. As shown in Fig. 1, this tilt in the drift of the charge carriers combined with a possible tilt in the detector by α, forces the holes to be collected on the p-side in a span of $\Delta x_h = \text{depth}(\mu^H_h B + \tan\alpha)$ and the electrons on the n-side in a span of $\Delta x_e = \text{depth}(\mu^H_e B - \tan\alpha)$. With $B = 2$ Tesla and chosing $\alpha = 6°$, the electrons and holes are collected over equal sized spans in x: $\Delta x_h = \Delta x_e = 50$ μm. Although this spread in x reduces the typical charge collected on a strip, it can be used to improve the position resolution by using the correlation of position with the amount of charge shared by neighboring strips. Our results, detailed below, show that this correlation is not lost in the reduction of data down to one bit per strip or washed out by electrical noise or Landau fluctuations. In our simulations we have ignored diffusion because the diffusion charge spread is much less than Δx_e and Δx_h at the detector voltages we expect to use.

The number of electron/hole pairs deposited along the particle's track is determined by the Landau distribution convoluted with a Gaussian to account for atomic binding effects [6]. This distribution depends on the mass and the momentum of the traversing particle which we take to be a 5 GeV charged pion. For high momentum particles, however, the distribution is not terribly sensitive to either the mass or the exact momentum. The distribution also depends on the depth of silicon considered. In our simulation we segment the particle's track into 15μm bins; Figure 2a shows the corresponding energy loss distribution in such a bin. Fig. 2b, peaking around 25000 elec/hole pairs, shows the distribution of the actual charge collected on the p-strip centered at $x = 0$ for a particle incident normally at $(x, y) = (0, 0)$, traversing the full 300μm, with the B-field turned off. To obtain the charge collected per unit time (binned in time buckets of $\Delta t = 0.5$ns), we segment each 15μ bin into 1μ buckets with each bucket of holes drifting in the electric field to the p-side and each bucket of electrons drifting to the n-side. The signal induced on a strip due a bucket of charge Q_{bucket} moving with velocity $\vec{v}$ is given by $I = Q_{\text{bucket}}\vec{W} \cdot \vec{v}$ where the weighting field $\vec{W} = -\vec{\bigtriangledown} V_w$ [7] is calculated by solving Laplace's equation, $\bigtriangledown^2 V_w = 0$, with 1) V_w=1V at the readout strip, 2) $V_w = 0V$ on all other strips, 3) $dV_w/dy = 0$ in the interstrip region, and 4) $dV_w/dx = 0$ at the sides of the detector. Given the periodic nature of the geometry and assuming that boundary effects are negligible, we only need to calculate one weighting field, at the central p-strip, for example. All other weighting fields are simple transformations of this field.

III. Description of Readout System

To get from the raw signal, $I = Q_{\mathrm{bucket}}\vec{W} \cdot \vec{v}$, to the final single bit per strip output of the discriminator, we convolute I(t) with our amplifier response function, add noise, impose a threshhold voltage, and, finally, we discard hits with discriminator firing times outside our data storage time-window. The amplifier response we chose, described as an CR-RC shaper, has the functional form $te^{-t/\tau}$. More complicated response functions could easily be accomodated. Fig. 3 shows an example of signals induced by a particle incident at $(x, y) = (0, 0)$, with average energy loss, before and after convolution with the amplifier. The tilt in the detector and the B-field induced Lorentz angle cause the holes to be collected on two neighboring p-strips. The signals were generated under 'nominal' conditions, defined in Table 2. Instead of adding noise to the raw or convoluted signal, we add to the threshhold voltage a random number from a Gaussian distribution with $\sigma = V_{MP}/\mathrm{SNR}$ where SNR is the signal-to-noise ratio and V_{MP} is the peak amplitude of the convoluted signal originating from a particle which deposits the most probable number of elec/hole pairs — about 25000 — along its track, with no fluctuations, with all the charge collected on one strip.

Table 2. Nominal Setup

Variable	Nominal
Pitch	50 μm
Width	10 μm
Depth	300 μm
B-Field	2 Tesla
Temperature	273°K
Si Type	n
$V_{\mathrm{depletion}}$	50 V
V_{bias}	90V
Detector Tilt	6°
Amplifier Response Time, τ	20 ns
Threshhold Voltage	25% V_{MP}
Signal-to-Noise	16
Data storage time window	[0,16ns]

For each different setup, about ten thousand particles are incident at $y = 0$ between $x = \pm$pitch/2 for p-side readout and between $x = \pm\text{pitch}/2 + \text{depth} \cdot \tan\alpha$ for n-side readout. For each incident particle, four strips centered at $x = -2\cdot$pitch, $-1\cdot$pitch, $0\cdot$pitch, and $+1\cdot$pitch are readout on each side of the detector. The output of one event is then the discriminator firing times, t_i, at (V(threshhold) + Noise(i)) for all strips, $i = 1 \ldots 8$, with signals which cross the threshhold. Those strips with signals not crossing threshhold are taken to be misses. In addition to signals not crossing threshhold, a strip is not 'hit' if t_i is not within the data storage time-window $[t_0, t_0 + \Delta t]$. Fig. 4 shows the time walk distributions for the nominal setup including Landau fluctuations: (a) the distribution of discriminator firing times on the p-side, given a single hit, (b) the earlier hit, given two hits on the p-side, (c) the later hit, given two hits on the p-side, (d)-(f) similarly, for the n-side. Imposing the nominal time window [0,16ns] to the distribution in Fig. 4 demonstrates how a single hit may become a zero hit event, adding to the inefficiency and how a double hit may become either a single or zero hit event. The final reduction of data assigns a '1' to strips with $t_0 < t_i < t_0 + \Delta t$; a '0' otherwise.

IV. Results

For each setup, for both the p and n-side, we extract the percentage of zero hits (i.e., the inefficiency), the ratio of single hit events to double hit events, and the mean and RMS of the $(x_{incidence} - x_{reconstructed})$ distribution for both single and double hit events. Since analog information is not kept, $x_{reconstructed}$ is the mean of the strip centers of the hit strips. For the p-side, $x_{incidence}$ is the intercept of the particle's track at $y = 0$; for the n-side, at $y =$ depth. The percentage of events with more than two hits on either the p or the n-side is typically less than 2% for all setups considered and is not separately displayed. The values extracted for the nominal setup are given in Table 3.

Table 3. Results for the Nominal Setup

Variable	p Side	n Side
Inefficiency	0.38±0.06 %	0.065±0.025 %
Single:Double	3.5	0.8
Single Hit RMS	12μm	9.6μm
Double Hit RMS	6.5μm	11μm
Single Hit Mean	16μm	29μm
Double Hit Mean	16μm	30μm

Recall that with $\alpha = 6°$ and $B = 2$ Tesla, $\Delta x_h = \Delta x_e = 50\mu$m (Fig. 1), so one would expect — with suitable $V_{\text{threshhold}}$ and data storage time-window — mostly single and double hits. If we can also assume that the 50μm region $-25 < x_{incidence} < 25\mu$m can be segmented into two distinct regions, one contributing exclusively to single hit events, one to double hit events, then the effective pitch for single and double hit events is

$$P_{\text{eff}}^{\text{single}} = \left(\frac{\text{Single : Double}}{\text{Single : Double} + 1}\right) \text{ Pitch}$$

and

$$P_{\text{eff}}^{\text{double}} = \left(\frac{1}{\text{Single : Double} + 1}\right) \text{ Pitch},$$

respectively, with corresponding resolutions (i.e., RMS's) of

$$\sigma^{\text{single,double}} = \frac{P_{\text{eff}}^{\text{single,double}}}{\sqrt{12}}.$$

A reasonably ideal situation would then be to have Single:Double = 1, giving $P_{\text{eff}}^{\text{single}} = P_{\text{eff}}^{\text{double}} = 25\mu$m and $\sigma^{\text{single}} = \sigma^{\text{double}} = 7\mu$m. The values for the nominal setup for the n-side tell us how close we can get to this ideal scenario: The inefficiency is very low; the percentage of events with more than two hits is less than 2%; and Single:Double ≈ 1. The single and double hit resolutions, however, are not 7μm, but approximately 10μm, giving an effective pitch of 35μm rather than the ideal 25μm. Therefore, the correlation of position with the amount of charge shared by neighboring strips persists, but Landau and electrical noise have caused the single and double hit regions to overlap somewhat. The p-side is not able to reach the ideal ratio of single hits to double hits because time slewing turns many double hits into single hits (Fig 4), but the correlation between $x_{incidence}$ and charge sharing is slightly better than for the n-side.

The nominal setup defined in Table 2 is an estimate of the parameters for the detectors at the SSC. Component to component variability and variations over time of certain parameters make it prudent to study how the values in Table 3 change as we deviate from the nominal setup. In the studies defined in Table 4 we have varied one to three parameters at a time, fixing all others to their nominal value.

Table 4. Definition of Studies

Variable(s)	Range Considered	Figures
I. Detector Tilt	4, 6, 8, 10°	Fig. 5
II. Amplifier Response Time, τ	10, 15, 20, 25, 30 ns	Fig. 6
III. Threshhold Voltage	20, 25, 30, 35, 40% V_{MP}	Fig. 7
IV. Signal-to-Noise Ratio	8, 12, 16, 20, 24	Fig. 8
V. Data storage $[t_0, t_0 + \Delta t]$:		Fig. 9
t_0	0, 1, 2, 3 ns	
Δt	10-30 ns	
VI. Radiation Study:	n, 50V, 90-120V	Fig. 10, 11
	p, 50V, 90-120V	
Si Type, $V_{\mathrm{depletion}}$, V_{bias}	p, 75V, 95-140V	
	p, 100V, 120-160V	
	p, 125V, 145-180V	

Figure 5 shows the sensitivity of our system to variations in the detector tilt angle α. Several aspects of Fig. 5 are common to all of our figures: (i) The p-side inefficiency is significantly worse than the n-side (Fig. 5a); (ii) the ratio of single hits to double hits is consistently higher on the p-side (Fig. 5b); and (iii) the single hit events on the p-side typically have the worst resolution, the double hits on the p-side the best resolution, and the n-side single and double hit resolutions are intermediate (Fig. 5c). All these prevalent qualities are due mainly to the slower charge collection on the p-side and, as discussed above, (i) and (ii) are correlated.

We sweep from an angle of $\alpha = 4°$, where $\Delta x_e = 60\mu$m and $\Delta x_h = 40\mu$m, to $\alpha = 10°$, where $\Delta x_e = 28\mu$m and $\Delta x_h = 71\mu$m. The slight decrease in inefficiency, on the n-side, as α increases is presumably due to the fact that there is less charge sharing between n-strips as α increases. Analogously, one might expect the inefficiency on the p-side to increase with α. This does not occur, suggesting that the inefficiency on the p-side is dominated by time-slewing not by signals which do not cross threshhold. Notice that although the single to double hit ratio on the p-side decreases by almost a factor of two going from $\alpha = 4°$ to $\alpha = 10°$, getting closer to the 'ideal' single to double ratio, there is no improvement in the single hit resolution.

Figure 6 shows the effect of varying the amplifier response time from 10 to 30ns. There is a steep increase in the inefficiency beginning around $\tau = 25$ns due to charge being collected outside our nominal data storage time window, [0,16ns].

With a 30ns amplifier response time, if a strip, before convolution, collected 25000 holes in the first nanosecond, the convoluted signal would not cross the nominal threshhold until about t = 8ns. The double hit resolutions, on both the p-side and n-side are relatively flat as τ varies, whereas the single hit resolutions have a relatively steep slope going from roughly 13μm resolution at τ = 30ns to 9μm resolution at τ = 10ns on both the p and the n-side. The means in Fig. 6d are quite flat indicating that component to component variability in τ will not affect the calibration: $x_{incidence} = x_{\text{reconstructed}} +$ mean. The means were also flat (i.e., $<$ 5μm range) as we varied $V_{\text{threshhold}}$, signal to noise ratio, and V_{bias} (for a fixed $V_{\text{depletion}}$). Between two extreme data storage time windows, [0,10ns] and [0,30ns], the mean, on the p-side, has a range of 15μm. More realistic constraints on $[t_0, t_0 + \Delta t]$, however, will reduce this range well below 5μm.

In Fig. 7, we sweep $V_{\text{threshhold}}$ from 20% of V_{MP} to 40% of V_{MP}. The inefficiency on the p-side goes above 1% at about $V_{\text{threshhold}}$ = 27% of V_{MP} and increases steeply.

In Fig. 8 the signal to noise ratio is varied from 8 to 24. The inefficiency on the p-side goes from about 1% at SNR = 12 up to about 3% at SNR = 10 and is relatively flat above 12. Below SNR = 12 there also appears to be a significant degradation in the spatial resolution. Constraints on the random counting rate of the discriminator will also require SNR>12.

In Fig. 9 we show how sensitive our system is to changes in the data storage time window $[t_0, t_0 + \Delta t]$. The duration of the window, Δt = 10ns to 30ns, is on the x-axis and each curve is labeled by $t_0 = 0, 1, 2,$ or 3ns. The functional form for the inefficiencies on the p and n-side (Fig. 9a and b, respectively) are similar. (The n-side efficiency, as always, is better by at least factor of two for almost all values of t_0 and Δt.) This functional form could have been ascertained from the time walk distributions in Fig. 4: To obtain the best efficiency one wants to center $[t_0, t_0 + \Delta t]$ about the (approximately symmetric) distributions Fig. 4a and b (for the p-side); so as Δt decreases the 'best' t_0 increases. Fig. 9a suggests that t_0 = 1ns may be a more conservative design target than $t_0 = 0$. At the nominal Δt = 16ns, the $t_0 = 0$ and t_0 = 1ns curves are equal; for $\Delta t >$ 16ns the $t_0 = 0$ curve is marginally better than the t_0 = 1ns curve, but both inefficiencies are well below one percent. For $\Delta t <$16ns, however, the $t_0 = 0$ curve has a significantly steeper slope than the t_0 = 1ns curve. Fig. 9d shows the single and double hit resolutions, for both the p and n-sides, for t_0 = 0ns. Although not realistic, it is interesting to note that if Δt could be as large as 26ns then the p-side would reach its most ideal setup. The single and double hit resolutions, again, are not 7μm, but approximately 8.75μm, giving $P_{\text{eff}} \approx 30$. The reason the ideal setup for the p-side is 'better' than the ideal setup for the n-side (w/ $P_{\text{eff}} \approx 35$) is demonstrated in the time walk distributions (Fig. 4): Before imposing the data storage time window, the p-side 'naturally' had roughly equal amounts of single and double hits, whereas the n-side had roughly twice as many double hits. The p-side ideal setup, with its unrealistic data storage time window, achieves Single:Double$\approx$ 1 mostly via the threshhold voltage; whereas, the n-side reaches its ideal Single:Double$\approx$ 1, by turning double hits into single hits with the data storage time window, degrading the correlation between $xincidence$ and charge sharing.

As our silicon microstrip detectors are irradiated with hadrons the effective doping concentration, hence $V_{\text{depletion}}$, changes. As donors are removed and acceptors are created, the detectors eventually invert. Pitzl *et al.* [8] showed how the effective doping concentration of a silicon microstrip detector changed with proton irradiation (Fig. 10a). The transition from n-type silicon to p-type occurred at about $\Phi_p = 1.5 \cdot 10^{13}/\text{cm}^2$. With an expected hadron fluence of about $5 \cdot 10^{12}/\text{cm}^2/\text{yr}$, at a radius of 15cm, this inversion is expected in about three years, given the nominal SSC luminosity of $10^{33}/\text{cm}^2/\text{s}$. Fig. 10b shows the electric field in the detector for both n-type and p-type silicon at $V_{\text{depletion}} = 50\text{V}$ and $V_{\text{bias}} = 90\text{V}$ demonstrating how the signal on the p-side will on average be slower for the inverted detector, whereas the signal on the n-side will on average be faster. Fig. 11a shows the inefficiency, for the p-side, versus V_{bias} for n-type silicon at $V_{\text{depletion}} = 50\text{V}$ and for p-type silicon at $V_{\text{depletion}} = 50, 75, 100$, and 125V. The inefficiency on the n-side was less than 0.1% for all setups considered and is not shown. Fig. 11b shows more explicitely the V_{bias} which is necessary to keep the inefficiency on the p-side at (or below, for the nominal setup) 1%. Fig. 11c shows the corresponding single and double hit resolutions on the p-side. Fig. 11d show the inefficiency on the p-side versus V_{bias} for p-type silicon with $V_{\text{depletion}} = 75\text{V}$ for data storage time windows with $\Delta t = 16\text{ns}$ and $t_0 = 0 - 5\text{ns}$. This figure demonstrates that there may be alternatives to increasing V_{bias} as $V_{\text{depletion}}$ continues to increase with irradiation.

V. Conclusions

We have investigated, using a Monte Carlo program, the expected performance of the SDC silicon detectors. We find that the resolution expected is about 10μm and that the inefficiency is less than 1% for realistic operating conditions. These values, as well as systematic shifts in assigned mean positions are not very sensitive to small changes in operating parameters, for example discriminator threshholds or circuit rise times.

The thresholds for the n and p sides of the detector should be separately controlled to allow individual optimization for detectors which will experience large radiation doses. The ability to change the timing of the data storage window, by a few nanoseconds, on the p-side would allow some additional flexibility to optimize efficiency.

Finally, for single-sided detectors the use of an n-sided device may be more radiation resistant than the more common p-sided detector.

VI. References

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