Charge collection with binary readout from a test beam perspective

M.Vos [a,b] J.Bernabeu [a], Z.Dolezal [e], J.E.Garcia Navarro [a], P.Kodys [e], G.F.Moorhead [d], M.D'Onofrio [c], P.Reznicek [e]

[a] *IFIC, U. Valencia/CSIC, Spain*

[b] *Universiteit Twente, The Netherlands*

[c] *University of Geneva, Switzerland*

[d] *University of Melbourne, Australia*

[e] *Charles University, Prague, Czech Republic*

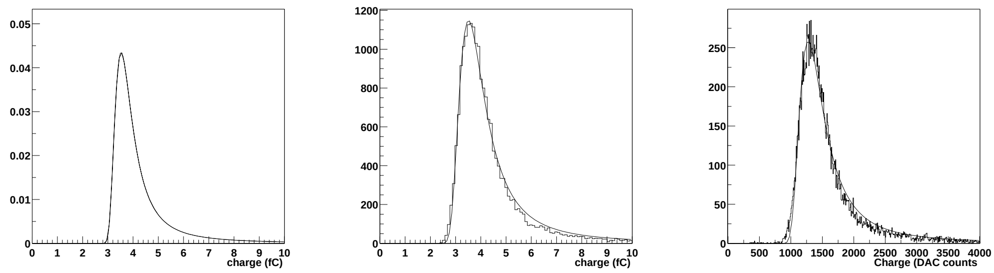
Abstract

Some aspects of charge collection in the binary readout scheme are discussed in the light of beam test results of recent SCT prototypes.

1 Introduction

The energy deposition due to the passage of charged particles (ionisation) is described to first order by Landau theory [1]. For 180 GeV/c charged pions perpendicularly incident on a 285 micron Silicon wafer approximately 22,300 electron-hole pairs are created. The most probable energy loss predicted by Landau theory is found to be rather accurate. The experimentally observed energy *distributions*, however, are generally significantly broader than the Landau prediction, see for example [2]. Various semi-phenomenological models exist that provide a good description of the observed distributions [2–4].

The electrical field in the wafer causes the electrons and holes to drift to opposite sides of the detector. In p^+n detectors, holes drift towards the strips, while the electrons are collected on the backplane. Assuming the signal is the sum of the charges of all created holes, the expected peak of the charge distribution is $\sim$ 3.6 fC. In figure 1 the charge distributions for 180 GeV/c charged pions are compared: the theoretical Landau distribution (a), a Monte Carlo model GEANT4 [3–5] (b) and the experimental result for the charge collected in 300 micron thick detectors with analog readout (c). In binary systems, with on-chip discrimination, it is easier to determine the median charge than the peak of the charge distribution. The expected median charge is 3.9 from Landau theory and 4.0 fC from GEANT4.



(a) (b) (c)

Fig. 1. Charge distribution deposited by 180 GeV/c charged pions perpendicularly incident on a 285 μm Silicon wafer. The smooth line superposed on the histogram is the fit results. *(a)* Landau theory, fit results: MPV = 3.58 fC, width/MPV = 6.3 % *(b)* Geant, fit results: MPV = 3.58 fC, width/MPV = 9.2 % *(c)* Experimental result. Fit results: width/MPV = 9.6 %

Many prototype SCT modules have been tested in test beams in recent years [7–12]. The median charge for a range of bias voltages is routinely measured. For a large number of non-irradiated SCT modules of different types, the median collected charge is 3.4 ± 0.1 fC [7,6] [1] at the nominal bias voltage of 150 Volts. The error represents the root-mean-square over the sample of modules. If the bias voltage is raised to 300 Volts, the collected charge increases by about 0.12 ± 0.05 fC to 3.5 ± 0.1 fC. From these measurements it is concluded that for maximum charge collection the median charge is 3.5 ± 0.1 fC.

In this note an attempt is made to account for the 0.5 fC that is apparently not collected.

2 Calibration & Measurement errors

The calibration is an important step in the interpretation of the beam test results. All modules submitted are fully characterized in-situ inmediately before the beam data is taken. The response curve - the relation between input charge and output voltage of the front end stage - is determined using the internal calibration circuit of the ABCD chip.

[1] Significantly different measurements have been published for previous beam tests, most notably the KEK beam test - $Q_m(150V) \sim 3.7$ fC. The difference is at least partly explained by the more refined calibration correction applied in more recent beam tests.

The calibration circuit produces a voltage step that is applied to a capacitor at the input of the amplifier. The result is a fast pulse with a settable, *known* total charge. Of course, the calibration circuit itself has a limited precision.

The calibration capacitors vary slightly depending on the processing of the batch of chips. Therefore, on each wafer test structures of oxide layers are measured. The calibration of the chips corresponding to that wafer is corrected according to the results of these measurements. Typical correction factors are in the range from 1.05 to 1.20.

Measurements of the stability of the calibration DACs under temperature variations were presented in reference [13]. Small variations with temperature were found. The spread in the measured output from the DACs of different chips from the same batch is 1.4 %. The central value is in good agreement with the nominal value for a temperature of $\sim 0^o$ C.

The variation of the calibration from one chip to the next was evaluated in the May and July beam test by pointing the beam to areas of the detector read out by different chips and measuring the median charge of each chip separately. For non-irradiated modules the spread was measured to be of the order of 4% (0.1 fC). In practice, the signal-to-noise, the ratio of median charge and the equivalent noise charge, removes most of the calibration dependence.

The Front End of the SCT modules is very fast in order to cope with the high bunch crossing rate in the LHC. This brings about the necessity to control the timing of the readout at the level of nanoseconds. In the beam test this is achieved by measuring the delay between the scintillator trigger and the next rising edge of the clock. Offline, the optimum time window is selected for each module. The width of this window is chosen to be 10 ns, balancing the loss of statistics and the error introduced by the smearing of the timing. Thus, the charge measured in the beam test corresponds to the average over the pulse shape in a 10 ns interval around the peak. The underestimate of the median charge introduced by the time window is well below 0.1 fC. This is confirmed by charge measurements in a beam with an LHC-like time structure [8].

The time window effect is small compared to the uncertainty in the calibration. Therefore, no attempt is made to correct the median charge measurement. Instead, an error of 0.1 fC is quoted.

3 Charge sharing

The binary readout scheme is essentially single-strip. The charge deposited on neighbouring readout strips cannot be recovered by clustering. Three mechanisms that lead to leakage of the signal to neighbouring strips are discussed here:

Cross talk between channels is dominated by the capacitive coupling between adjacent strips in the detector. The inter-strip and strip-to-backplane capacitance have been measured, finding values of $\sim$ 1 pF/cm and 1.3/768 nF, respectively. The design value of the coupling capacitor to the Front End electronics is larger than 20 pF/cm. From figure 2 one can estimate the frac-

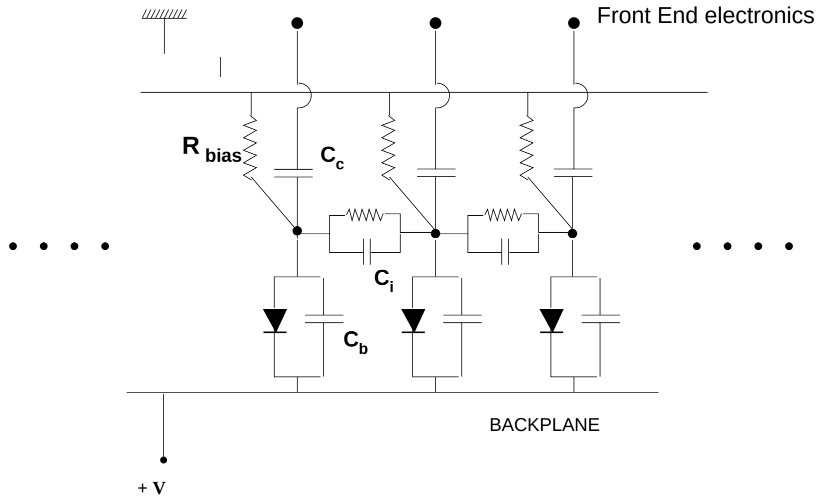


Fig. 2. Equivalent diagram of three strips with their capacitive connections to the Front-End electronics, the neighbouring strips and the backplane.

tion of the signal that is induced on the principal strip and its neighbours. Ignoring the impedance of the amplifier and assuming the capacitor on the hybrid that joins the detector backplane and HV ground is sufficiently large:

$$I_{amp} = \frac{I_s C_c}{C_c + C_i + C_b} \tag{1}$$

Using values for the coupling, interstrip and strip-to-backplane capacitances of $C_c = 120$ pF, $C_i = 6$ pF and $C_b = 1.7$ pF the fraction of the signal induced on neighbouring strips is expected to be of the order of 6%, ie typically 0.2-0.3 fC. Multiplying by the median deposited charge, 4.0 fC, the median charge loss due to cross talk becomes $\sim$ 0.26 fC.

Diffusion A second mechanism that leads to charge sharing is the diffusion of the charge carriers while drifting through the silicon. These effects have been studied in some detail in beam test of prototype modules, see for example [7,8]. For perpendicularly incident particles, its effect is limited to a rather small region exactly between two readout strips. Measurements of the spatial distribution of the drifting carriers [14] find a FWHM of $\sim$ $6\mu m$ at a bias voltage of 120 Volts. Only in strong magnetic fields and when particles are incident at an angle does this effect become important over a larger region.

δ **electrons** The tail of the Landau distribution is formed by events where a large momentum is transferred in a collision between the incident particle and an electron. Electrons with energies of several tens to hundreds of kilo-electronVolts can travel significant distances - up to $100\mu m$ in the silicon. These so-called δ-electrons (also known as δ-rays or knock-on electrons) deposit energy along their path through ionisation. Energetic δ-electrons that travel large distances in the direction perpendicular to that of the primary particle are rather rare, but have a significant effect on the resolution, see for example [15].

The effect of δ-electrons on the median collected charge is estimated using the GEANT4 simulation. When only charge deposited close (within 5 μm) to the primary track is taken into account, the number of events in the tail of the distribution decreases. Nevertheless, the median of the distribution is not significantly affected. Therefore, even though δ-electrons form an important ingredient in understanding the shape of the distribution, and other observables like the average cluster size, charge sharing due to δ-electrons has no measurable effect on the median charge.

The fact that the charge sharing due to the diffusion of the carriers is limited spatially can be used to try to disentangle its effect from charge sharing due to the remaining two mechanisms. In the test beam, tracks are reconstructed using a beam telescope made up of Silicon strip detectors with analog read-out. The tracks are projected on the DUT with high precision (better than 5 micron). The probability to create multi-strip clusters and the median charge are determined for two cases:

- in the first sample all tracks are accepted, ie the position of the track with respect to the two nearest strips is uniformly distributed
- the second sample only contains those tracks that project onto a region of $\pm$ 20 microns around the strip. The effect of diffusion is expected to be small in these events.

The amount of leakage of charge to adjacent strips is best characterised by the probability of multi-strip clusters. Figure 3 shows the probability to create multi-strip clusters[2] measured on both samples. Clusters with signal over threshold in more than one channels are rather rare (of the order of 5 %) at the operating threshold (1 fC), but the fraction grows strongly for lower thresholds.

[2] not to be confused with the multi-strip cluster fraction that has been reported in many test beam publications

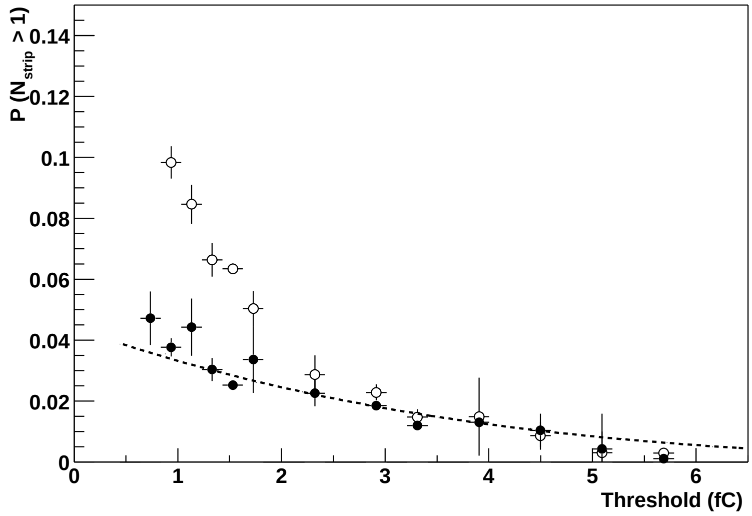


Fig. 3. Probability to create two-strip cluster versus threshold for perpendicularly incident 180 GeV/c charged pions. Open markers correspond to all tracks. The filled markers have been determined using a sub-sample of tracks that are incident close to a strip.

The open markers represent the results of the first sample. All three mechanisms contribute to the multi-strip clusters in this case. The result of the second sample is shown with filled markers. The selection of tracks close to the strip eliminates the contribution of diffusion.

The dashed line represents the result of a model calculation based on GEANT4 [3] of the multi-strip probability due to δ-electrons for tracks incident close to a readout-strip. The coincidence between the model and the results from the second sample (filled markers) is rather good.

The multi-strip cluster probability at high thresholds is essentially independent of the track inter-strip position, indicating that diffusion plays no significant role at high threshold. The charge loss due cross-talk is generally small. Therefore, the multi-strip events at high charge are thought to be due to δ-electrons. At low threshold, the two curves diverge: diffusion becomes dominant below $\sim$ 1 fC. A number of observations reinforce this conclusion. The multi-strip clusters attributed to diffusion show a very narrow, nearly Gaussian residual distribution. The corresponding distribution for the events where the track was incident close the strip is nearly flat. Moreover, the diffusion component is found to decreases with increasing detector bias [4] , while no significant dependence on bias voltage (after full depletion) is observed in

[3] The probability is calculated from a comparison of the threshold and the charge deposition of δ-electrons in an 80 μm wide region starting at a distance of 20-60 μm from the track

[4] This is expected as the spatial distribution of the charge carriers becomes narrower

the remaining multi-strip clusters.

For both samples the median charge has been determined. The difference between both results is a measure of the charge that leaks to neighbouring strips due to diffusion. For all module types, the median charges obtained in the two samples differ by 0.13-0.16 fC.

The effect of the remaining two charge sharing mechanism cannot be measured in the beam test. For the charge loss due to cross talk our best guess is the 0.26 fC quoted before.

Thus, the total effect of charge sharing on the median charge is expected to be approximately 0.4 fC.

4 Median versus Most Probable charge

In the binary readout scheme the charge that is most easily measured is the median of the distribution, whereas with analog electronics the most probable charge is a more natural choice. The relation between both charges depends on the details of the distribution, which is affected by charge losses to adjacent strips.

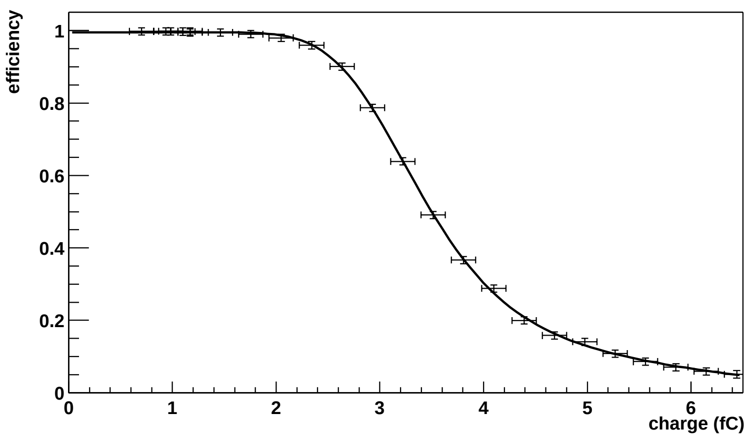


Fig. 4. S-curve for a non-irradiated K5 module. The fit function, a skewed error function, is described in [9,11]

Figure 4 shows the S-curve - efficiency versus discriminating threshold. The points with error bars represent the efficiency measurements at different threshold in the beam test. The continuous line is a fit with a skewed error function. The derivative of the S-curve in figure 5 gives an idea of the charge distribution in both types of modules. The points with error bars correspond to the difference of two consecutive measured data points divided by their charge

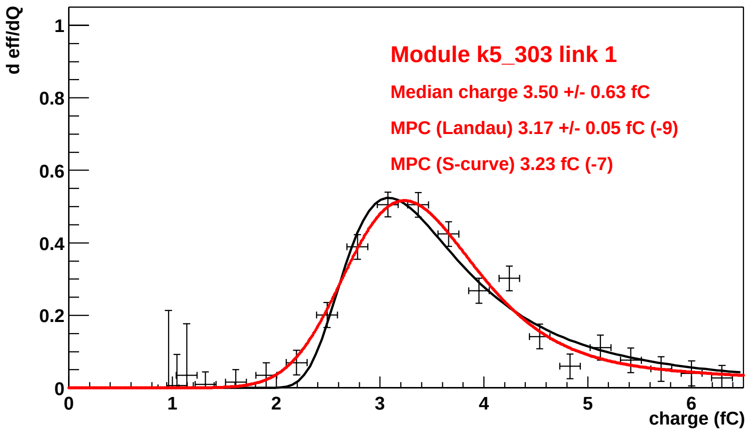


Fig. 5. Numerical derivative of figure 4. The dark line represents a fit with a Landau distribution. The lighter line is the numerical derivative of the S-curve fit. The most probable charges obtained from both fits are listed in the figure, as well as the median charge.

distance. Two curves are drawn in the same figure: the red curve is the numerical derivative of the skewed error function, the black curve is a fit of a Landau distribution to the data points. The most probable charge, found as the peak of the Landau fit, is smaller than the median charge, from the fit to the S-curve, by 8-15 %. This should be compared to the 12 % one finds from integrating the charge distribution in figure 1 (a).

5 Irradiated modules

After irradiation to high fluences of high-energy particles (typically, modules are irradiated to $3 \cdot 10^{14}$ 24 GeV protons/cm^2) a high bias voltage is needed to reach full charge collection. This is due to a combination of the high depletion voltage, the formation of the p-n junction on the opposite side of the detector after type-inversion, trapping of charge carriers in lattice defects [5]. A detailed discussion of the charge collection mechanism is outside the scope of this note. Also, the test beam results are far less conclusive for irradiated modules [7–10]. In this section, a number of observations are briefly discussed.

The calibration of irradiated modules has relatively large uncertainties. An increase (to 3 %) is observed in the spread in the calibration DACs. The absolute value of the DAC output is within 5 % of the nominal value at 0^o C. The spread in the median charge measured on different chips of the same

[5] the bias voltage dependence is thought to arise from the dependence of the trapping probability on collection time, see for example [16]

module increases to nearly 10% (0.3 fC) [6].

In general, the median charge is measured to approach that of non-irradiated modules for the maximum bias voltage of 500 Volts. The variations between results on irradiated modules are of the order of the chip-to-chip spread. An error of 0.3 fC is therefore proposed for charge measurements on irradiated modules.

The charge sharing profiles for all tracks (open markers) and those that are incident close to a strip (filled markers) of irradiated modules at a bias voltage of 500 Volts are shown in figure 6. Both curves are very similar to that of the non-irradiated modules in figure 3 down to a threshold of 1 fC. For lower thresholds the probability to create a multi-strip cluster rises much more steeply than for similar non-irradiated modules. This could indicate an increase in the cross talk, but can also be explained from the higher noise charge (and channel-to-channel gain variations). The current measurements do not provide conclusive evidence for either effect.

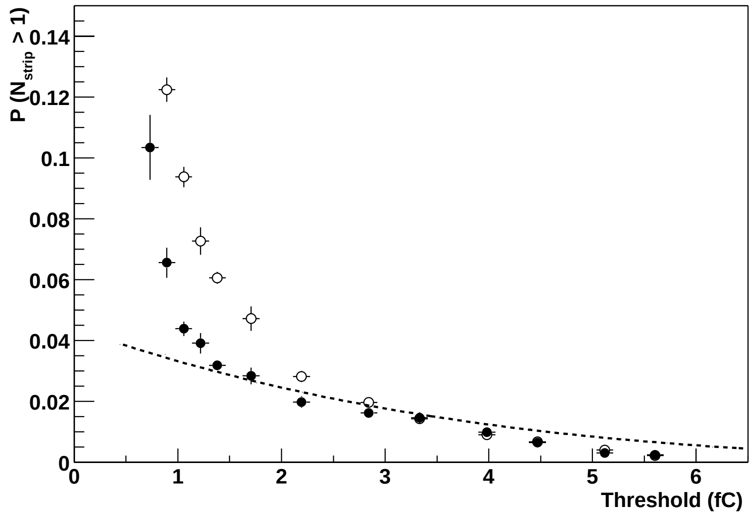


Fig. 6. Probability to create multi-strip cluster versus threshold for perpendicularly incident 180 GeV/c charged pions. Open markers correspond to all tracks. The filled markers have been determined using a sub-sample of tracks that are incident close to a strip. The dashed line represents a model prediction based on GEANT4.

[6] The DAC output and median charge measurements are correlated. Correcting the charges by the DAC step measurements mentioned before improves the uniformity, suggesting that the larger spread in median charges is at least partly due to random variations in the components of the calibration circuit

6 Conclusions

For MIPs perpendiculary incident on a 285 μm thick p^+n detector the expected *deposited* signal is 4.0 fC.

Measurements of the *collected* signal in beam tests of SCT prototypes yield a median charge of 3.5 ± 0.1 fC. Systematic effects related to the way the charge is measured, notably the time window, are controlled to well below 0.1 fC.

A possible explanation for the apparent lost charge is that in the binary readout scheme charge leaking to neighbouring strips is not recovered. Three charge sharing mechanisms have been discussed. Diffusion of the charge carriers leads to charge sharing only in a narrow region between two readout strips. This property is used to measure the effect on the median charge: $\sim$ 0.14 fC. The effect on the median charge of the remaining charge sharing mechanisms cannot be measured in the test beam. Measurements of the inter-strip and strip-to-backplane capacitance yield a prediction of the charge loss due to cross talk of the order of 6 % (0.26 fC). Long range δ-electrons are expected to have no measurable effect on the median charge.

Summarizing, the median *collected* charge is expected to be lower than the *deposited* charge by $\sim$ 0.4 fC. The resulting prediction of 3.6 fC is to be compared to the experimentally measured median charge of 3.5 $\pm$ 0.1 fC.

The calibration is found to vary from chip to chip at the level of 4 % (1 sigma). In irradiated modules the variation reaches 5-10 %.

The median of the measured *collected* charge distribution is 12 $\pm$ 3 % larger than the most probable signal.

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