

# Charge Collection Efficiency Measurements for Segmented Silicon Detectors Irradiated to $1 \times 10^{16} \text{ n cm}^{-2}$

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**Abstract**—Plans are well advanced for a phased upgrade program of the Large Hadron Collider (LHC) at CERN. An improvement of nearly a factor of ten to reach a luminosity close to  $10^{35} \text{ cm}^2 \text{ s}^{-1}$  is the target of the upgraded machine, called the Super LHC (SLHC). The innermost tracker devices in the SLHC will be exposed to hadron radiation doses in excess of  $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ . The detectors to be used in the tracker system of the SLHC experiments need therefore to be qualified to these extreme fluences. Segmented n-strip silicon detectors made with thin ( $140 \mu\text{m}$ ) and standard ( $300 \mu\text{m}$ ) p-type substrates have been irradiated with neutrons to different fluences up to  $1 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$  and characterised in term of charge collection efficiency measurements using high speed (40 MHz, 25 ns shaping time) analogue electronics. These measurements are the first direct comparison between the charge collection performance of thin and thick silicon microstrip devices as a function of different fluences relevant to future supercolliders. They also set a reference for the maximum collected charge by segmented sensors made in planar technologies (microstrip and pixel detectors) at these extreme doses, allowing for predictions on the functionality of silicon detectors that can operated in the inner tracking system of SLHC experiments.

**Index Terms**—Position sensitive particle detectors, radiation detectors, radiation hardening, silicon radiation detectors.

## I. INTRODUCTION

THE upgrade of the present LHC to a machine with an almost tenfold increase in luminosity [1] will require detectors with high readout speed, fine granularity and extreme radiation hardness. Silicon detectors, already used for the innermost tracking layers of all four the LHC experiments (ALICE, ATLAS, CMS and LHCb), are a likely choice for the upgrade because they satisfy the criteria of speed and granularity. In order to be qualified for the SLHC, silicon sensors will also have to meet the severe requirements in radiation tolerance imposed by the unprecedented luminosity of the new machine. The inner sensors are expected to withstand a charged hadron radiation dose in the order of  $10^{16} \text{ 1 MeV neutron equivalent (n}_{\text{eq}}) \text{ cm}^{-2}$  [2]. A prediction of the performance of silicon detectors after very high doses is needed to guide the technology choices of the experiments in the SLHC. The signal over noise (S/N) ratio is an effective measure of the detector performance. The noise

of a particular detector system depends on the electronics and on the detector geometry, which can be estimated during its design phase. The measurement of the charge collection efficiency (CCE) as a function of the fluence is the key parameter to calculate the S/N ratio for a given detector system and therefore to determine its performance (track efficiency, purity) after irradiation. The aim of the present work is to measure the degradation of the signal of silicon sensors up to the dose anticipated for the inner layer of the SLHC experiments. The experimental measurements here presented have been performed after neutron irradiation of the silicon detectors. Irradiation with charged particles (protons) will be required to confirm the very encouraging results here reported.

## II. EFFECTS OF IRRADIATION ON THE COLLECTED CHARGE

The charge released by a minimum ionising particle crossing a silicon detector is proportional to the path length of the particle in the sensor. The typical thickness for the silicon sensors used in high energy physics experiments is  $300 \mu\text{m}$ , which is a good compromise between low mass, mechanical stability and size of the signal (about  $23000 \text{ e}^-$  for the most probable value of the minimum ionizing particle energy distribution). The damage produced by hadron irradiation to the silicon crystal changes several electrical properties of the detectors. In particular the full depletion voltage ( $V_{\text{fd}}$ ) and the reverse current ( $I_{\text{r}}$ ) increase considerably after heavy irradiation, while the collected charge is significantly reduced by charge trapping [3]. The radiation induced deficit of the CCE can be expressed by the following equation:

$$N_{e,h}(t) = N_{e,h}(0) \exp\left(-\frac{t_c}{\tau_{e,h}}\right) \quad (1)$$

where  $N_{e,h}$  is the number of collected charges (electron or holes respectively),  $N_{e,h}(0)$  is the number of ionised electrons and holes,  $t_c$  is the collection time and  $\tau_{e,h}$  is the electron and hole effective trapping time. The charge carrier effective trapping time decreases as a function of fluence like

$$\frac{1}{\tau_{e,h}} = \beta_{e,h} \phi_{eq} \quad (2)$$

where  $\phi_{e,h}$  the 1 MeV neutron equivalent fluence and  $\beta_{e,h}$  are the trapping damage constant for electrons and holes respectively. The measured values are  $3.7 \times 10^{-16} \text{ cm}^2 \text{ ns}^{-1}$  for  $\beta_e$  and  $5.7 \times 10^{-16} \text{ cm}^2 \text{ ns}^{-1}$  for  $\beta_h$  [4], [5]. From (1) it is clear

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that shorter  $t_c$  provides substantial advantages in terms of collected charge.

It is well known that n-type silicon becomes effectively p-type after a dose of irradiation that can be considered small for modern hadron collider applications (a few  $10^{13} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ ). The electric field of inverted n-type silicon detectors is stronger under the  $\text{n}^+$  contact [6], like in p-type bulk detectors. If segmented devices are read out from the  $\text{n}^+$  side (n-in-n detectors), they will benefit from a shorter  $t_c$  due to the collection of the electron current (with three times higher mobility than holes, before saturation of the velocity occurs) transported by the high electric field. This is more readily achieved by using n-side readout on p-type substrates (n-in-p), where no inversion takes place with irradiation and the main electric field is always located on the original  $\text{n}^+ - \text{p}$  junction side. In order to take advantage of the shorter  $t_c$  with respect to the more standard p-side readout of n-type silicon, we proposed the use of p-type bulk detectors for optimal radiation tolerance [7].

The trapping of charge carriers can be so important with increasing fluences that the collection distance (the longest distance from which carriers generated by ionisation can reach the readout electrodes) could become shorter than the detector thickness. This implies that thinner detectors can be as efficient as standard ones after severe irradiation. Moreover, it has also been proposed that thinner silicon sensors would be able to collect more charge due to a possible strengthening of the electric field in the area adjacent to the readout electrode with respect to thicker devices [8].

### III. EXPERIMENTAL METHODS AND RESULT

#### A. CCE Measurements After Irradiation

Small size ( $\sim 1 \times 1 \text{ cm}^2$ )  $80 \mu\text{m}$  pitch (128 strips) silicon AC coupled detectors have been designed by Liverpool and processed by Micron Semiconductor on  $4''$  wafers  $300 \mu\text{m}$  and  $140 \mu\text{m}$  thick. A few detectors were irradiated at the TRIGA II nuclear reactor of the University of Ljubljana [9]. An estimated error of 10% is given on the dosimetry. The sensors have been characterised after irradiation with the charge collection efficiency measurement set-up in the semiconductor detector centre of the University of Liverpool (LSDC). The set-up includes a radioactive  $^{90}\text{Sr}$  source to provide fast electrons with an energy deposition in silicon comparable to minimum ionising particles, a scintillator trigger and a readout based on the SCT128 40 MHz analogue chip [10]. The system is calibrated with a nonirradiated  $300 \mu\text{m}$  thick sensors with known most probable energy deposition ( $23000e^-$ ). The thin and thick detectors have been irradiated in pairs to the nominal fluences of 0.5, 1.6, 3 and  $10 \times 10^{15} \text{ n cm}^{-2}$ . A further  $300 \mu\text{m}$  thick detector has been irradiated successively to perform a second measurement at  $3 \times 10^{15} \text{ n cm}^{-2}$ .

After irradiation the sensors have been stored at temperatures well below  $0^\circ\text{C}$  to suppress annealing. It is well known that irradiated silicon detectors are subject to an annealing process with a reduction of the reverse current with time after irradiation and a significant increase of the full depletion voltage after a short period ( $\sim 10$  days at room temperature) of recovery [3].

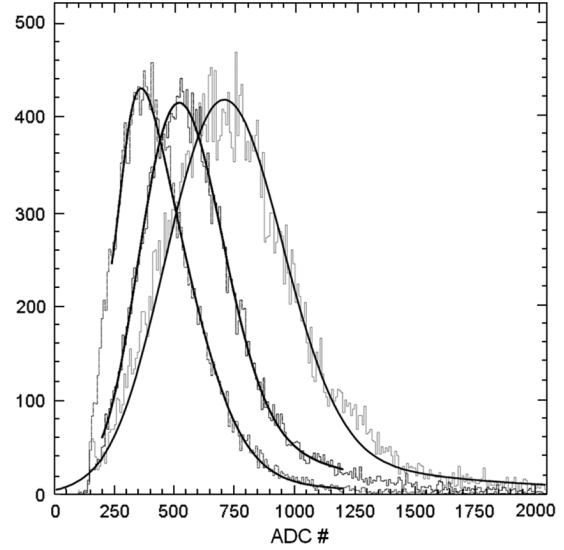


Fig. 1. Energy distribution of a minimum ionising particle (m.i.p.) crossing a nonirradiated and two irradiated detectors. The distribution of the nonirradiated  $300 \mu\text{m}$  thick detector (the higher in the figure) has a most-probable value of  $23000e^-$  that is used to calibrate the system.

The reduction of the reverse current has a positive effect on the detector operation because it could reduce the shot noise component in the electronics and the risk of thermal runaway (uncontrolled increase of the current due to self heating) of the detectors. The increase of the full depletion voltage (known as *reverse annealing*) has always been considered detrimental to the sensor operations: the  $V_{\text{fd}}$  was commonly linked to the CCE, in the sense that both quantities were thought to saturate at the same voltage, as for nonirradiated devices. The substantial increase of  $V_{\text{fd}}$  with annealing time would entail a corresponding decrease of the charge collected at a given voltage below  $V_{\text{fd}}$ . The annealing is exponentially dependent on the temperature and it is practically suppressed below  $0^\circ\text{C}$ . The irradiated detectors have been shipped to Liverpool in cold boxes and stored below freezing temperatures apart for the time elapsed to bond them to the readout electronics ( $< 2$  h at room temperature).

The measurements were performed in a freezer at about  $-25^\circ\text{C}$ . The thin and thick detectors have been measured in identical conditions after the four irradiation doses.

Figs. 2–5 show the collected charge as a function of the bias voltage [CC(V)]. Figs. 2 and 3 show the CC(V) of the thin and thick detectors increasing with bias at almost the same rate until the charge collected by the  $140 \mu\text{m}$  thick devices saturates, while the charge collected by the thick detectors keeps increasing with voltage. These measurements clearly show that the collection distance after the corresponding doses in silicon is over  $140 \mu\text{m}$  at adequate operating voltages, and that the increase of the detector electric field with lower bias voltages does not differ significantly for the two thicknesses.

Fig. 4 shows the CC(V) for three detectors irradiated to  $3 \times 10^{15} \text{ n cm}^{-2}$ . The two detectors irradiated together (one standard and one thin) show a similar rise of the collected charge with voltage up to 950 V. The last point of the thicker detector was taken at 990 V, where the device started to show instabilities in the current and excess noise. A second  $300 \mu\text{m}$  thick detector

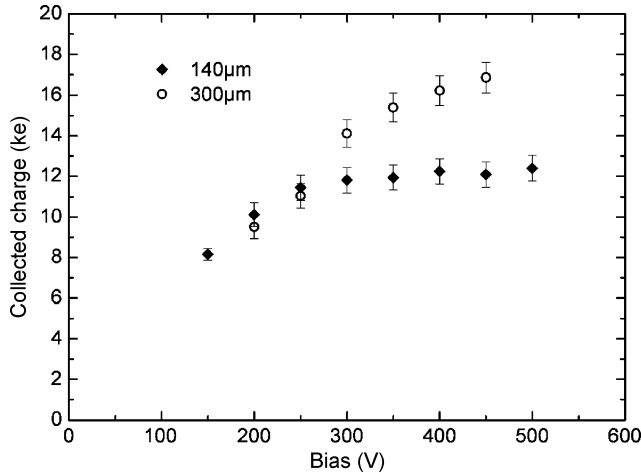


Fig. 2. Collected charge as a function of the bias voltage for thin ( $140 \mu\text{m}$ ) and thick ( $300 \mu\text{m}$ ) detectors irradiated to  $5 \times 10^{14} \text{ n cm}^{-2}$ .

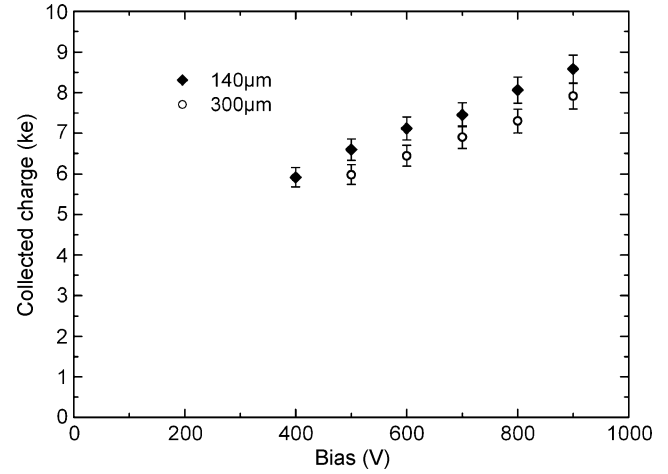


Fig. 5. Collected charge as a function of the bias voltage for thin ( $140 \mu\text{m}$ ) and thick ( $300 \mu\text{m}$ ) detectors irradiated to  $1 \times 10^{16} \text{ n cm}^{-2}$ .

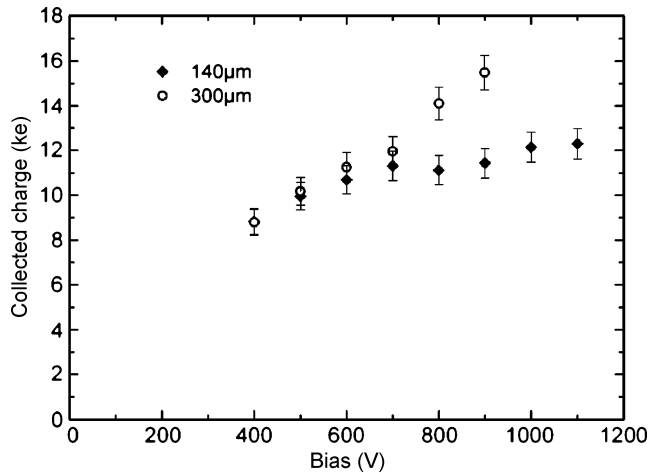


Fig. 3. Collected charge as a function of the bias voltage for thin ( $140 \mu\text{m}$ ) and thick ( $300 \mu\text{m}$ ) detectors irradiated to  $1.6 \times 10^{15} \text{ n cm}^{-2}$ .

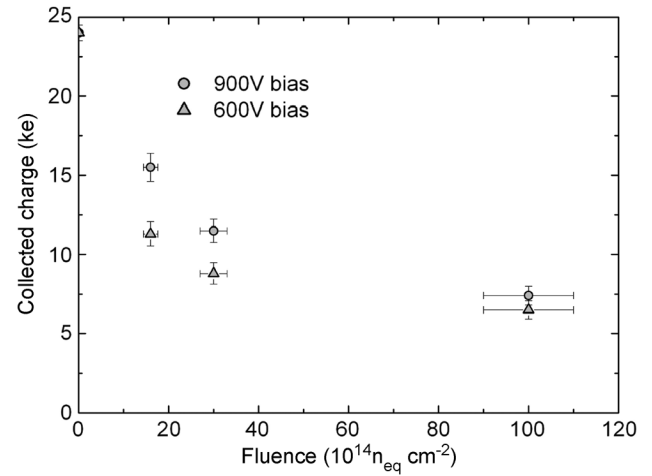


Fig. 6. Degradation of the collected charge with neutron equivalent fluence for microstrip silicon detectors irradiated with reactor neutrons.

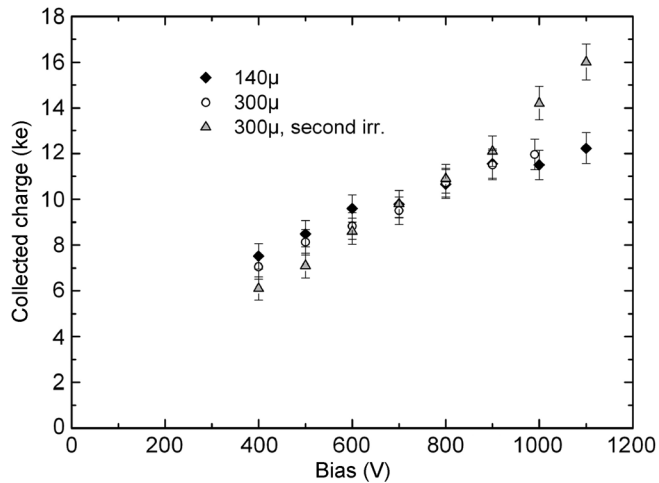


Fig. 4. Collected charge as a function of the bias voltage for thin ( $140 \mu\text{m}$ ) and thick ( $300 \mu\text{m}$ ) detectors irradiated to  $3 \times 10^{15} \text{ n cm}^{-2}$ .

was irradiated to the same nominal dose to complete the measurements at very high voltage. A difference can be noticed at

lower bias voltages where this second thick detector exhibits a slightly smaller charge collection that could be explained by differences in the actual dose between the two irradiation runs (an uncertainty of about 10% from the nominal dose is expected). At 1000 V volts and above this second 300  $\mu\text{m}$  thick detector exhibits higher CCE than the thin one, indicating that even after  $3 \times 10^{15} \text{ n cm}^{-2}$  the charge collection distance in silicon is longer than 140  $\mu\text{m}$  at very high bias.

Fig. 5 shows the CC(V) for the detector pair irradiated to  $1 \times 10^{16} \text{ n cm}^{-2}$ . The collected charge as a function of bias at any voltage up to 900 V has a similar trend for both thicknesses, with about 10% higher charge collected by the thin device. The onset of current run-away prevented measurements at higher bias voltages. Based on the results of the measurements after  $3 \times 10^{15} \text{ n cm}^{-2}$  it is inferred that the collection distance in silicon after the higher dose has fallen below 140  $\mu\text{m}$ .

Fig. 6 shows the degradation of the collected charge as a function of the neutron dose measured with these planar microstrip detectors. A remarkable value of collected charge well in excess of 7000  $\text{e}^-$  is measured after  $1 \times 10^{16} \text{ n cm}^{-2}$  at bias voltages above 600 V.

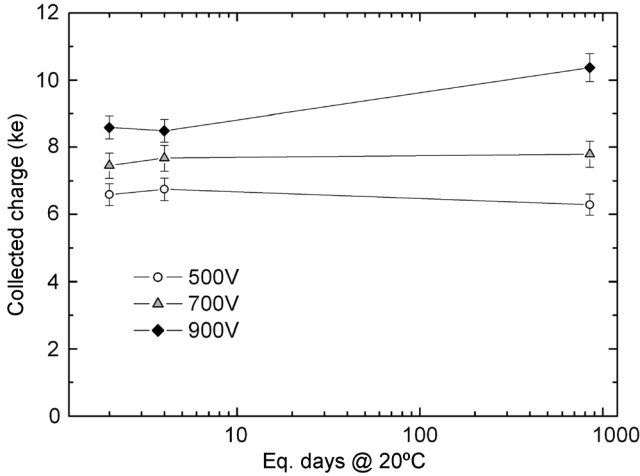


Fig. 7. Collected charge at three different bias voltages with the 300  $\mu\text{m}$  thick detector as a function of time at 20  $^{\circ}\text{C}$  after irradiation to  $1 \times 10^{16} \text{ n cm}^{-2}$ .

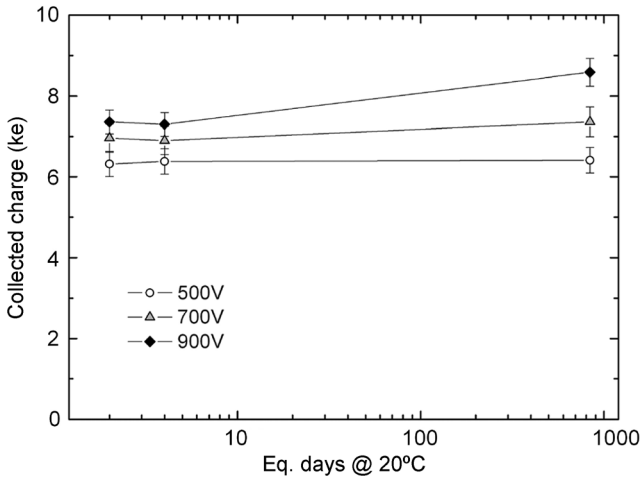


Fig. 8. Collected charge at three different bias voltages with the 140  $\mu\text{m}$  thick detector as a function of time at 20  $^{\circ}\text{C}$  after irradiation to  $1 \times 10^{16} \text{ n cm}^{-2}$ .

### B. Annealing Studies of the Collected Charge

Accelerated annealing studies have been performed to investigate the CCE as a function of time after irradiation to  $1 \times 10^{16} \text{ n cm}^{-2}$  with thick and thin detectors. It has been shown [11], [12] that the CCE with n-side readout, p-type bulk silicon detectors does not suffer the considerable changes with time found on the  $I_r$  and the  $V_{fd}$  after proton or neutron irradiation. These results are in disagreement with the assumption that the charge collection follows the  $V_{fd}$  after irradiation, which would predict a substantial decrease of the charge collected at voltages below  $V_{fd}$ . The results shown in [11] and [12] were obtained with standard thickness detectors (300  $\mu\text{m}$ ) irradiated to lower doses.

To simulate the effect of the room temperature annealing over several years at room temperature, the detectors were heated to 80  $^{\circ}\text{C}$  for periods of one or two hours. The acceleration factor at this temperature is about 7400 times with respect to 20  $^{\circ}\text{C}$  [3]. Figs. 7 and 8 show the charge collected at three different voltages (500, 700 and 900 V) as a function of time after irradiation for thin and thick detectors irradiated to the maximum dose. It is evident that no decrease of the collected signal is found after annealing. On the contrary an improvement of about 15% (20%)

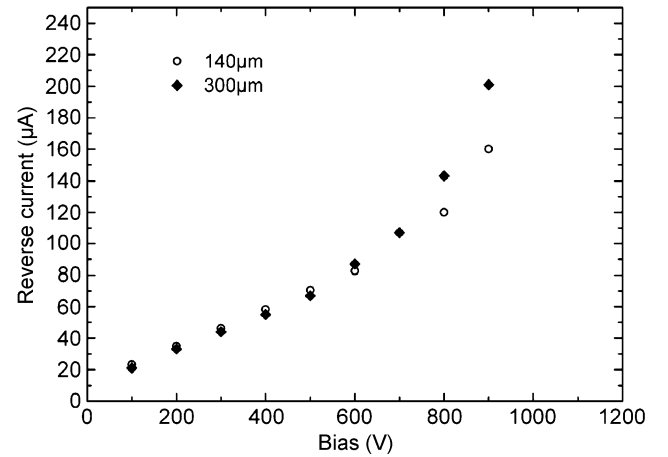
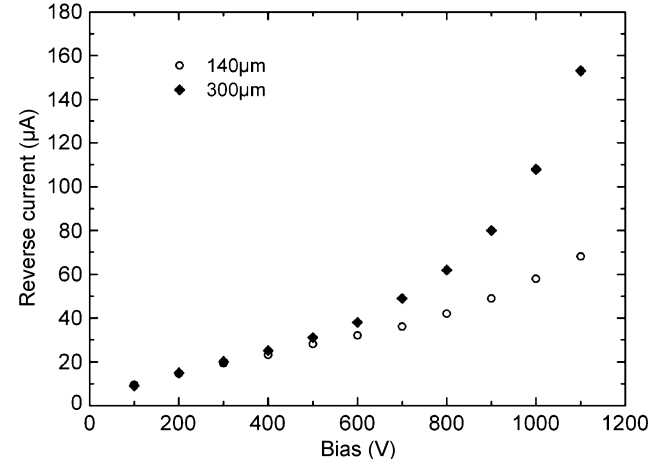
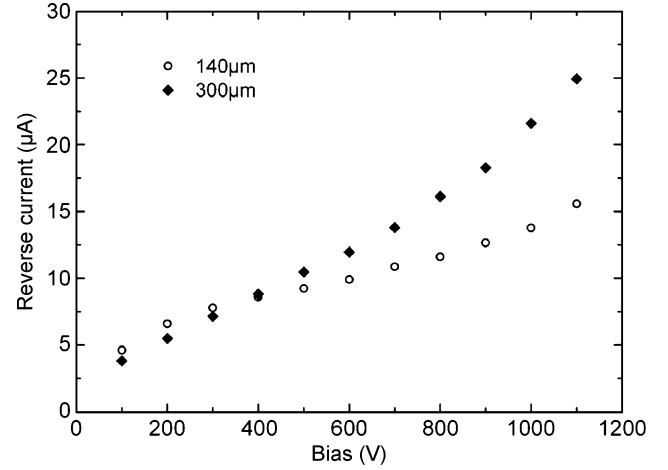


Fig. 9. Reverse current as a function of the bias voltage for pairs of 300  $\mu\text{m}$  and 140  $\mu\text{m}$  thick detectors irradiated to 1.6, 3 and  $10 \times 10^{15} \text{ n cm}^{-2}$  (from top to bottom, respectively).

is measured with the thick (thin) detector, probably due to the beneficial annealing of the electron trapping constant [4].

### IV. REVERSE CURRENT

The reverse current of irradiated silicon detectors increases linearly with fluence (see e.g. [3]). The radiation induced defects of the silicon crystal act as current generation centres.  $I_r$  is proportional to the number of the contributing centres, therefore to the depleted volume of the sensors. As said before, in detector systems  $I_r$  contributes to the increase of the electronics noise and

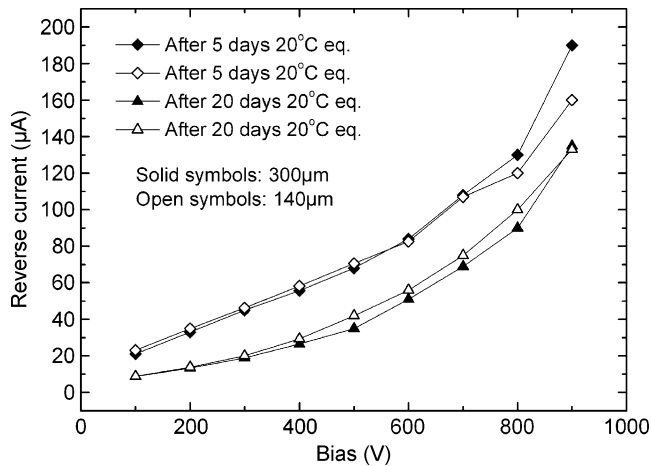


Fig. 10. Reverse current as a function of the bias voltage for the 300  $\mu\text{m}$  and 140  $\mu\text{m}$  thick detectors irradiated to  $1 \times 10^{16} \text{ n cm}^{-2}$  after 5 and 850 days of room temperature equivalent annealing.

to the risk of thermal runaway. Efficient cooling is therefore essential for detectors that are developing elevated currents. Lower  $I_r$  is expected with thin detectors due to their smaller volume.

Fig. 9 shows the comparison of the reverse current as a function of the bias voltage (IV) of irradiated thin and thick detectors.

After  $1.6 \times 10^{15} \text{ n cm}^{-2}$  the current of the thick sensor starts to become higher than the thin one at about 500 V. It should be noticed that the charge collected by the thick sensors is higher above 600 V. This is an indication that above 500 V the volume contributing to both the reverse current and the charge collection becomes deeper than 140  $\mu\text{m}$  after this irradiation dose.

The two sensors irradiated to  $3 \times 10^{15} \text{ n cm}^{-2}$  exhibit almost the same currents up to about 600 V. For higher bias voltages the current drawn by the thick detector becomes about 1.5 times larger up to 900 V. The thick sensor collects more charge above 800 V. It can be noticed that at higher voltages a steeper increase of the IV is found. It is possible that contributions to the current other than the bulk generated one occur under these bias conditions. For example, small differences in the temperature of the silicon bulk could be responsible for this increase. Further studies will be required to separate the contribution of the volume current from other possible effects.

The IV curves of the devices irradiated to  $1 \times 10^{16} \text{ n cm}^{-2}$  are similar excluding the values at 800 and 900 V, where a sharper increase of the IV of the thick detector is measured. Fig. 10 shows the IV of these same detectors after an annealing time equivalent to 5 and 850 days at room temperature. It can be noticed that these curves exhibit the same trend (sharper increase at high voltage for the thick detector) after a five days annealing, but they are essentially equal in the last measurement.

## V. CONCLUSION

A direct comparison of the charge collection properties of thin (140  $\mu\text{m}$ ) and standard (300  $\mu\text{m}$ ) silicon detectors has been carried out for the first time after heavy hadron irradiation. The measurements have been successfully performed after four different doses of neutron irradiation up to  $1 \times 10^{16} \text{ cm}^{-2}$ . Although further studies at different intermediated doses will be

required to precisely determine the degradation of the CCE with fluence, the present results show that n-side readout detectors can be an option for the tracking layers at small radii in the future SLHC experiments. The size of the signal after  $10^{16} \text{ n cm}^{-2}$  would still allow efficient tracking provided that a low noise system ( $\leq 800 \text{ e}^-/\text{channel}$ ) is designed and high voltage and efficient cooling can be routed to the detectors.

It has also been shown that standard thickness devices (300  $\mu\text{m}$ ) can collect more charge than 140  $\mu\text{m}$  ones up to doses as high as  $3 \times 10^{15} \text{ n cm}^{-2}$  at very high bias voltages. On the other hand, it has been shown that no significant advantage at lower voltages is found with thin detectors in term of charge collection. Even after the higher dose, where the charge collection distance is below 140  $\mu\text{m}$  for any applicable bias, the charge collected by thin devices is no more than 10% higher than standard thickness detectors.

The  $I_r$  measurements have shown that after severe irradiation doses the reverse current of thin and thick detectors are essentially the same up to very high bias voltages.

The annealing of the charge collection efficiency with time after irradiation has been measured with thin and thick detectors after the higher dose. The measurements confirm that the reverse annealing of the CCE does not take place with n-side readout p-type bulk detectors for both types of device.

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