Charge collection efficiency measurements for segmented silicon detectors irradiated to $1x10^{16}$ n cm^{-2}

Gianluigi Casse, Antony Affolder and Philip P. Allport, *Member, IEEE*

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} cm^2 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 $1x10^{16}$ n_{eq} 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 (140µm) and standard (300µm) p-type substrates have been irradiated with neutrons to different fluences up to $1x10^{16}$ n cm^{-2} and characterised in term of charge collection efficiency measurements using high speed (40MHZ) analogue electronics. These measurements are the first direct comparison between the charge collection performances 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.**

I. INTRODUCTION

THE upgrade of the present LHC to a machine with an almost tenfold increase in luminosity [1] will require detectors with high read-out 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 radiation dose in the order of 10^{16} 1MeV neutron equivalent (n_{eq}) cm^{-2} [2]. A prediction of the performances 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 performances. 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 performances (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.

Manuscript received November 4, 2007. G. Casse, A. Affolder and P.P. Allport are with the Department of Physics, University of Liverpool, Oxford St., L69 7ZE, Liverpool

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 300µm, which is a good compromise between low mass, mechanical stability and size of the signal (about 23000 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_{fd}) and the reverse current (I_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:

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

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:

$$\frac{1}{\tau_{e,h}} = \beta_{e,h}\phi_{eq} \tag{2}$$

where $\phi_{e,h}$ the 1MeV neutron equivalent fluence and $\beta_{e,h}$ are the trapping damage constant for electrons and holes respectively. The measured values are 6.2 x 10^{-16} cm^2 ns^{-1} for β_e and 4.1 x 10^{-16} cm^2 ns^{-1} for β_h [4]. From (1) it is clear that shorter t_c provides substantial advantages in term of collected charge.

It is well known that n-type silicon becomes effectively p-type after a dose of hadron irradiation that can be considered small for modern hadron colliders applications (a few 10^{13} n cm^{-2}). The electric field of inverted n-type silicon detectors is stronger under the n^+ contact [5], like in p-type bulk detectors. If segmented devices are read-out from the 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) transported by the high electric field. This is more readily achieved by using n-side read-out 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 n^+-p junction side. In order to take advantage of the shorter t_c with respect to the more standard p-side read-out of n-type silicon, we proposed the use of p-type bulk detectors for optimal radiation tolerance [6].

The trapping of charge carriers can be so important with increasing fluences that the collection distance (the longest distance from which carrier generated by ionisation can reach the read-out electrodes) could become shorter than the detector thickness. This implies that thinner detector 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 read-out electrode with respect to thicker devices [7].

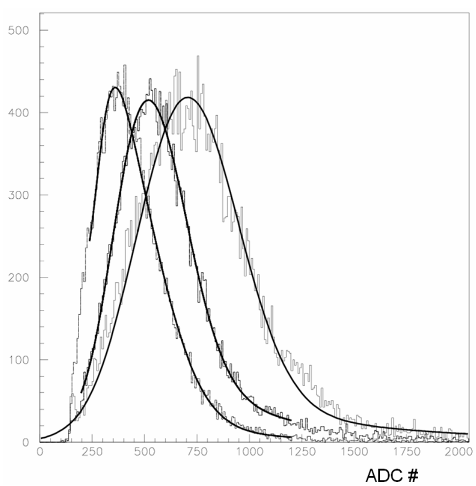

Fig. 1: Energy distribution of a minimum ionising particle (m.i.p.) crossing a non-irradiated and two irradiated detectors. The distribution of the non-irradiated 300µm thick detector (the higher in the Figure) has a most-probable value of 23000e⁻ that is used to calibrate the system.

III. EXPERIMENTAL METHODS AND RESULT

A. CCE measurements after irradiation

Small size (~1x1 cm2) 80µm pitch (128 strips) silicon AC coupled detectors have been designed by Liverpool and processed by Micron Semiconductor on 4” wafers 300µm and 140µm thick. The detectors were irradiated at the TRIGA II nuclear reactor of the University of Ljubljana to four doses up to 1×10^{16} n cm^{-2}. 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}Sr source to provide fast electrons with an energy deposition in silicon comparable to minimum ionising particles, a scintillator trigger and a read-out based on the SCT128 40MHz analogue chip [8]. The system is calibrated with a non irradiated 300µm 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 10×10^{15} n cm^{-2}. A further 300µm thick detector has been irradiated successively for completing the measurements at 3×10^{15} n cm^{-2}.

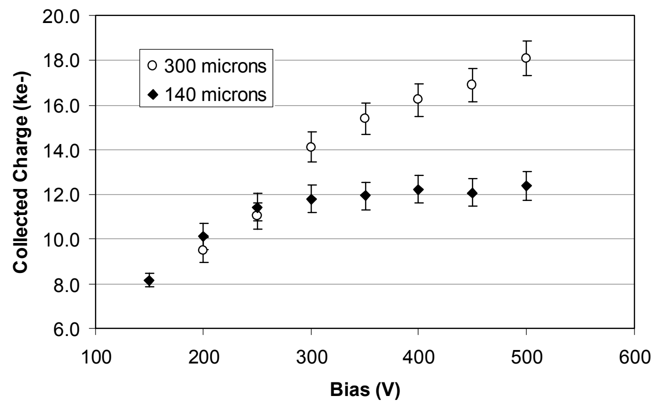

Fig. 2: Collected charge as a function of the bias voltage for thin (140µ) and thick (300µ) detectors irradiated to 5×10^{14} n_{eq} cm^{-2}.

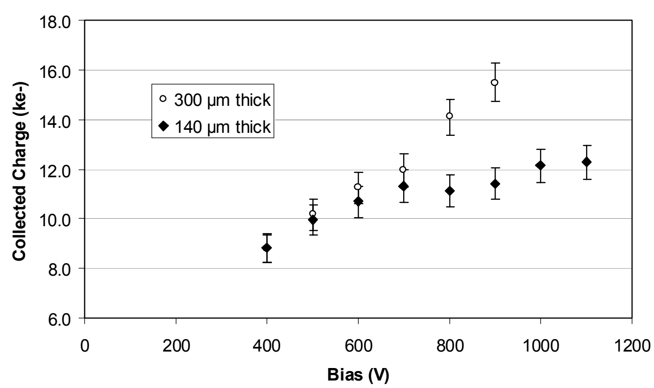

Fig. 3: Collected charge as a function of the bias voltage for thin (140µ) and thick (300µ) detectors irradiated to 1.6×10^{14} n_{eq} cm^{-2}.

After irradiation they have been stored at temperatures well below 0°C to suppress annealing. It is in fact well known that irradiated silicon detectors are subject to an annealing process whit a reduction of the reverse current with time after irradiation and a significant increase of the full depletion voltage after a short period (~10 days at room temperature) of recovery [3]. 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_{fd} was commonly linked to the CCE, in the sense that both quantities were thought to saturate at the same voltage, as for non-irradiated devices. The substantial increase of V_{fd} with annealing time would entail a corresponding decrease of the charge collected at a given voltage below V_{fd}. The annealing is exponentially dependent on the temperature and it is practically suppressed below 0°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 read-out electronics (<2h at room temperature).

The measurements were performed in a freezer at about -25°C. The thin and thick detectors have been measured in identical conditions after the four irradiation doses.

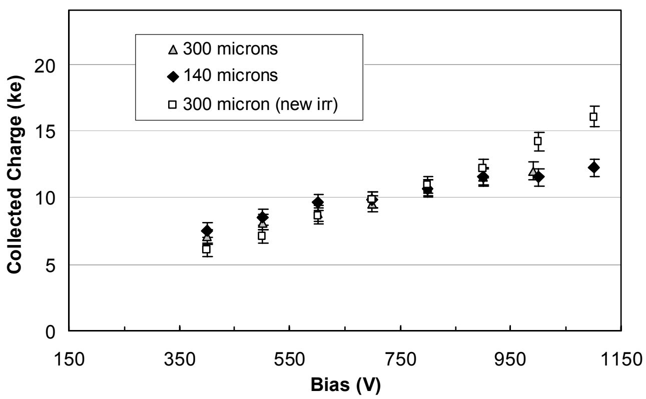

Fig. 4: Collected charge as a function of the bias voltage for thin (140µ) and thick (300µ) detectors irradiated to $3x10^{15}$ n_{eq} cm^{-2}.

Fig. 2,3,4 and 5 show the collected charge as a function of the bias voltage (CC(V)). Fig. 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 140µm 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 140µm at adequate operating voltages, and that the increase of the detector electric field with lower bias voltages doesn't differ significantly for the two thicknesses.

Fig. 4 shows the CC(V) for three detectors irradiated to $3x10^{15}$ 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 950V. The last point of the thicker detector was taken at 990V, where the device started to show instabilities in the current and excess of noise. A second 300µm thick detector 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 1000V volts and above this second 300µm thick detector exhibits higher CCE than the thin one, indicating that even after $3x10^{15}$ n cm^{-2} the charge collection distance in silicon is longer than 140µm at very high bias.

Fig. 5 shows the CC(V) for the detector pair irradiated to $1x10^{16}$ cm^{-2}. The collected charge as a function of bias at any voltage up to 900V 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 $3x10^{15}$ n cm^{-2} it is expected that the collection distance in silicon after the higher dose has fallen below 140µm.

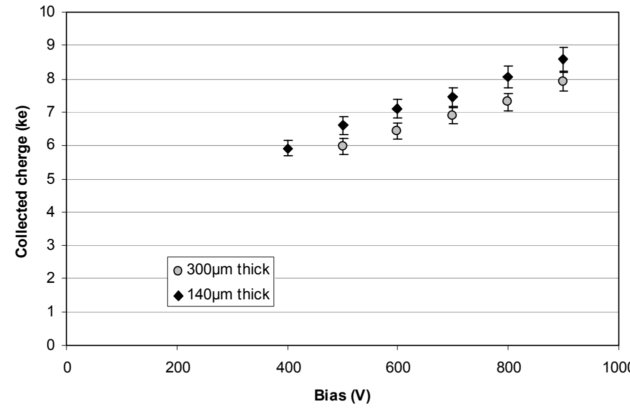

Fig. 5: Collected charge as a function of the bias voltage for thin (140µ) and thick (300µ) detectors irradiated to $1x10^{16}$ n_{eq} cm^{-2}.

Fig. 6 shows the degradation of the collected charge as a function of the neutron equivalent fluence for segmented planar (microstrip) detectors irradiated with neutrons and 24GeV/c protons. A remarkable collected charge well above $7000e^{-}$ is measured after the fluence of $1x10^{16}$ n cm^{-2} at bias voltages above 600V.

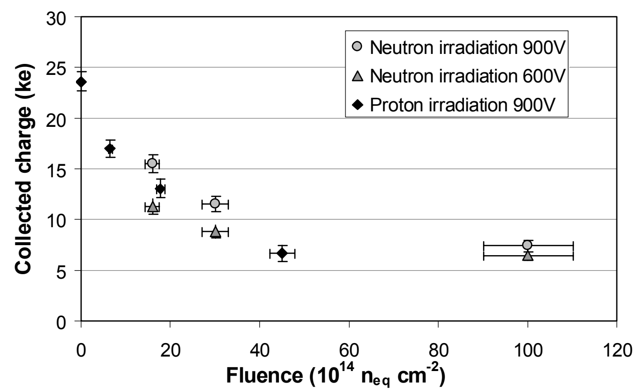

Fig. 6: Degradation of the collected charge with neutron equivalent fluence for microstrip silicon detectors irradiated with neutrons and 24GeV/c protons.

B. Annealing studies of the collected charge

Accelerated annealing studies have been performed to study the CCE as a function of time after irradiation to $1x10^{16}$ n cm^{-2} with thick and thin detectors. It has been shown [9, 10] that the CCE with n-side read-out, p-type bulk silicon detectors doesn't suffer the considerable changes with time found on the I_r and the V_{fd} after proton or neutron irradiation. This 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 [9, 10] where obtained with standard thickness detectors (300µm) irradiated to lower doses.

To simulate the affect of the room temperature annealing over several years at room temperature, the detectors were heated to 80°C for periods of one or two hours [3]. The acceleration factor at these temperature is about 7400 times with respect to 20°C. Fig. 7 and 8 show the charge collected at three different voltages (500, 700 and 900V) 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%) is measured with the thick (thin) detector, probably due to the beneficial annealing of the electron trapping constant [4].

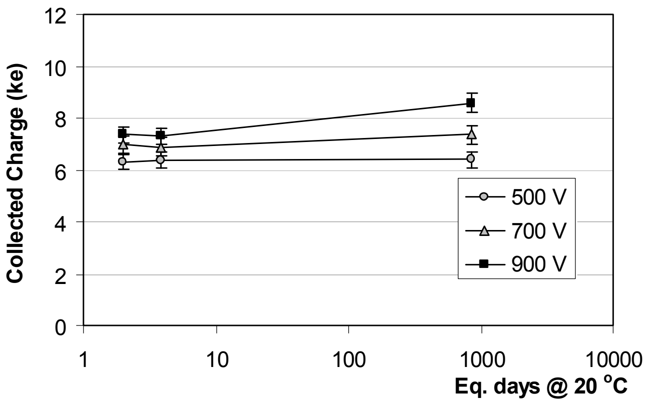

Fig. 7: Collected charge at three different bias voltages with the 300µm thick detector as a function of time at 20°C after irradiation to $1x10^{16}$ n_{eq} cm^{-2}.

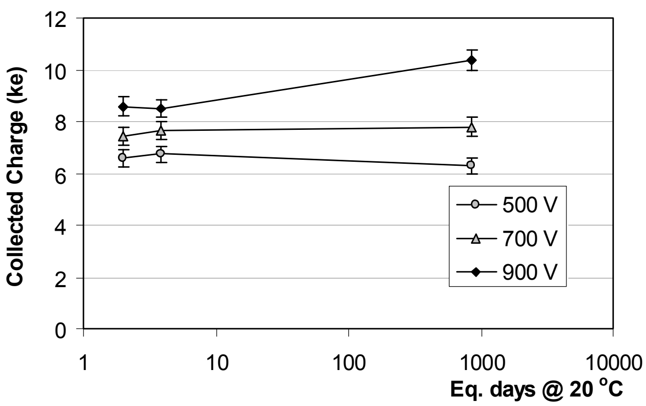

Fig. 8: Collected charge at three different bias voltages with the 140µm thick detector as a function of time at 20°C after irradiation to $1x10^{16}$ n_{eq} cm^{-2}.

IV. Conclusions

The direct comparison of the charge collection properties of thin (140µm) and standard (300µm) 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 $1x10^{16}$ cm^{-2}, which is the qualifying fluence for the innermost detectors in the future SLHC experiments. The direct measurement of the amount of charge collected by silicon sensors after such an extreme dose is now available for predicting their performances in vertex and tracker detectors in future SLHC experiments.

It has also been shown that standard thickness devices (300µm) can collect more charge than 140µm ones up to doses as high as $3x10^{15}$ n_{eq} 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 140µm for any applicable bias, the charge collected by thin devices is no more than 10% higher than standard thickness detectors.

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 doesn't take place with n-side read-out p-type bulk detectors for both type of devices.

Acknowledgement

This work was performed within the framework of the CERN-RD50 collaboration [11]. The authors would like to thank the team of the University of Ljubljana and especially Prof. V. Cindro, who performed the neutron irradiations, sometimes on short notice..

References

[1] O. Bruhning et al., LHC Project Report 626
[2] I. Dawson, "Radiation predictions at the SLHC and irradiation facilities,"ATLAS Tracker Upgrade Workshop, Liverpool, 6-8 Dec. 2006, http://www.liv.ac.uk/physics/AHLUTW/
[3] 3rd RD48 Status Report CERN LHCC 2000-009, LEB Status Report/RD48, 31 December 1999.
[4] G. Kramberger et al., "Annealing studies of effective trapping times," *Nucl. Instr. Meth. A*, Vol. 571/3, pp. 608-611, February 2007.
[5] L.J. Beattie et al., "The electric field in irradiated silicon detectors," *Nucl. Instr. Meth. A*, Vol. 418/2, pp. 314-321, December 1998.
[6] G. Casse, P.P. Allport, M. Hanlon, "Improving the radiation hardness properties of silicon detectors using oxygenated n-type and p-type silicon," *IEEE Transactions on Nuclear Sci.*, 47, Vol. 3, pp. 527-532, June 2000.
[7] E. Fretwurst et al., "High energy proton damage effects in thin high resistivity FZ silicon," detectors *Nucl. Instr. Meth. A*, Vol. 552, pp. 124-130, October 2005.
[8] F. Anghinolfi et al., "SCTA-a rad-hard BiCMOS analogue readout ASIC for the ATLAS Semiconductor Tracker," *IEEE Transactions On Nucl. Sci.* 44, Vol. 3, pp. 2 98-302, June 1997.
[9] G. Casse, P.P. Allport, A. Watson, "Effects of accelerated annealing on p-type silicon micro-strip detectors after very high doses of proton irradiation," *Nucl. Instr. Meth. A*, Vol. 568, pp. 46-50, June 2006.
[10] G. Casse, P.P. Allport, A. Greenall, "Response to minimum ionising particles of p-type substrate silicon microstrip detectors irradiated with neutrons to LHC upgrade doses," *Nucl. Instr. Meth. A*, Vol. 581, pp. 318-321, October 2007.
[11] CERN/RD50 collaboration, Radiation hard semiconductor devices for very high luminosity colliders, http://rd50.web.cern.ch/rd50.