New Operation Scenarios for Severely Irradiated Silicon Detectors

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Recent charge collection measurements after severe hadron irradiation have proved that n-side readout segmented planar silicon detectors can successfully operate up to the doses anticipated for the innermost layers of the upgraded experiments in the future super LHC (sLHC) at CERN. The charge collected by the irradiated sensors is sufficient to guarantee a signal over noise (S/N) ratio above 10 even for the pixel layers located at the smallest radial distance from the beam line (less than 4 cm away). The signal depends on the applied bias and voltages as high as 1000V could be required to satisfy the minimum signal height for the most exposed detectors. The radiation at the doses of the pixel layers in the sLHC also cause an important increase of the reverse current The high bias voltages and reverse currents cause significant power dissipation and adequate cooling needs to be applied to limit the current well below the thermal-runaway level.

Besides, both the collected charge and the reverse current change with time after irradiation (annealing). The rate of the changes is a steep function of the temperature: higher temperature cause accelerated annealing. These changes can in fact been exploited to extend the operation time of the silicon sensors. The requirements in term of bias voltage, temperature of the detectors during operation and temperature scenario outside the operation time (to provide the optimised annealing to the sensors) are here presented and discussed.

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[1] Speaker

Introduction

The upgrade of the CERN-LHC accelerator (sLHC) will approach the unprecedented luminosity of ~ 10^{35}cm^{-2}s^{-1} [1]. The tenfold increase of the luminosity with respect to the present machine will lead to the replacement of the vertex and tracker detectors of the experiments to deal with the increased hit density. Higher granularity (to limit the channel hit occupancy) and radiation tolerant detectors will be required. Concerning this last aspect, very encouraging results have been obtained in the last few years that allow for optimism regarding the functionality of the sensors after the hadron doses anticipated for the sLHC [2-6]. Nevertheless the detectors must be operated at high bias voltage and draw a significant reverse current after severe irradiation, adding to the power consumption of the front-end electronics (already considerable due to the fine granularity). An important aspect of the running procedures in the future sLHC experiments will be the choice of the optimal bias voltage and of the temperature of the detectors during operation and shut down times. Data are already available to help designing these procedures for the vertex and tracker detectors at different radii. In order to estimate the performance of the irradiated sensors, a few methods can be followed. In non-irradiated silicon detectors all the charge created by ionisation is collected if the device is biased to its full depletion voltage (V_{FD}) or above (over-depletion). The ability of over-depleting a detector can be considered as an estimate of its efficiency. This has been used in the design phase of the microstrip sensors of the present tracker systems of the general purpose detectors of the LHC ([7, 8]). This method does not account for the trapping of the signal charge carriers or for the fact that acceptable performance can be achieved also with bias voltage values below V_{FD}.

A most direct estimate of the performance of the sensors is the measurement of the signal after irradiation. It is generally accepted that good tracking performance can be achieved with a signal over noise ratio of 10 or larger. The noise depends on the detector geometry and electronics chain while the signal degradation is a property of the silicon crystal. The knowledge of the signal height after the relevant irradiation fluence combined with the known properties of the readout electronics allows for an accurate estimation of the performance of a given detector system.

Changes of electrical properties with irradiation

The hadron radiation damage causes the change of the electrical properties of the silicon detectors. The effective space charge (N_{eff}), proportional to V_{FD}, increases linearly with fluence after an initial reduction. The reverse current (I_R) increase is also proportional to the radiation fluence. These changes have been parameterised [9] following a large number of measurements with silicon detectors up to fluences of about 1×10^{15} n_{eq} cm^{-2}, because at more elevated doses the high value of V_{FD} prevents depleting the devices. It should be noticed that I_R is an exponential function of the temperature, so low temperatures can be used to efficiently reduce the current.

The collected charge decreases after irradiation, for a given applied reverse bias, due to two effects: the increase of V_{FD} and the charge trapping at radiation induced defect centres. The increase of V_{FD} causes the reduction of the depleted volume for a given applied voltage below full depletion. In the following, only the signal generated by minimum ionising particles (mip's) is considered, because it is relevant to high energy physics applications. The charge generated by a mip is proportional to the path length of the particle in the sensitive volume of a silicon detector, consequently a reduction of the active volume corresponds to an equivalent diminution of the signal. The charge trapping centres introduced by the irradiation remove charge carriers from the signal current. The density of traps is assumed to increase linearly with fluence and the effective trapping time $\tau_{e,h}$ for electrons (e) and holes (h) changes like [10]:

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

where ϕ_{eq} is the 1MeV neutron equivalent fluence and $\beta_{e,h}$ is the proportionality constant for electrons and holes. The ratio of the collection time of the signal (t_S) to $\tau_{e,h}$ defines the amount of charge loss to trapping according to:

$$Q_{signal} = Q_0 e^{-\frac{t_S}{\tau_{e,h}}} \tag{2}$$

where Q_{signal} and Q_0 are the measured charge and the ionised charge in the active volume, respectively. From Eq. 2, it is clear that shorter t_S yield larger signal. The electron signal in irradiated silicon detectors is faster than the signal carried by holes. For this reason, it has been shown that reading out segmented detectors from the n^+ implant (n-in-n or n-in-p geometries) offer a substantial advantage with respect to the more standard diode configuration (p-in-n) after irradiation [2-6, 11, 12].

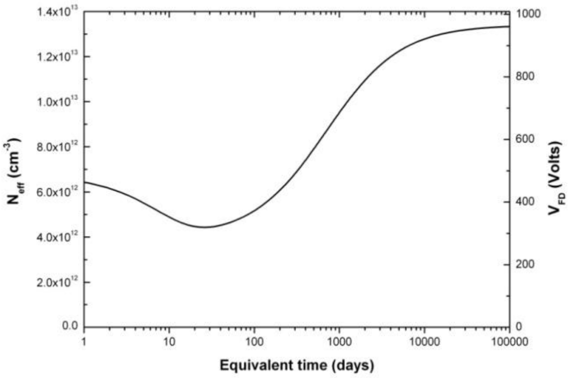

Figure 1: *Changes of N_{eff} (V_{FD}) with time after irradiation (at 20°C) for a p-in-n detector irradiated to $2x10^{14}$ n_{eq} cm^{-2}.*

Notable changes also take place with time after irradiation (annealing). The rate of these changes is an exponential function of temperature, so the annealing can be practically suppressed at 0°C or below, or accelerated at more elevated temperatures. The reverse current and the charge trapping probability reduce with time while V_{FD} has more complicated annealing behaviours, with an initial reduction (for about ten days at RT = 20°C) followed by a sizeable increase over several years at room temperature (RT). Figure 1 shows an example of the changes of V_{FD} (N_{eff}) over several years at RT, according to the parameterisation in [9] for a n-type bulk silicon sensor irradiated to 2×10^{14} n_{eq} cm^{-2}.

Experimental results

Charge collection after irradiation

Using the above parameterisations it is possible to predict the decrease of the signal as a function of the hadron fluence. In fact the measured signal is degraded by increasing hadron irradiation, as shown in Figure 2. Nonetheless, a signal larger than expected is measured after high fluences. Figure 3 shows the collected charge as a function of the bias voltage (CC(V)) for proton [11] and neutron [12] irradiated n-side readout detectors after very high doses, compared to the signal estimated using the accepted parameterisation for the charge trapping. The enhanced collected charge can be partly due to the failure of the parameterisation to describe the properties of the silicon detectors above 1×10^{15} n_{eq} cm^{-2}, but the large discrepancy between experimental data and the estimated maximum signal requires a different explanation.

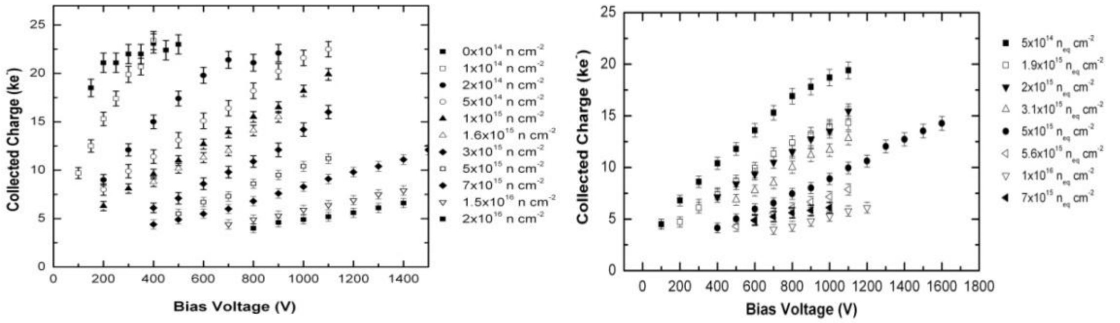

Figure 2*: Degradation of the collected charge as a function of the bias voltage (CC(V)) for neutron (left) and proton (right) irradiated segmented 300 µm thick n-in-p silicon sensors.*

This remarkable result is believed to be due to a charge multiplication effect at high electric field in irradiated segmented silicon sensors. This interpretation is supported by the results shown in Figure 4, where the CC(V) properties of a thin (140 µm) and a standard thickness (300 µm) silicon microstrip sensors have been measured after proton irradiation to 5×10^{15} n_{eq} cm^{-2}.

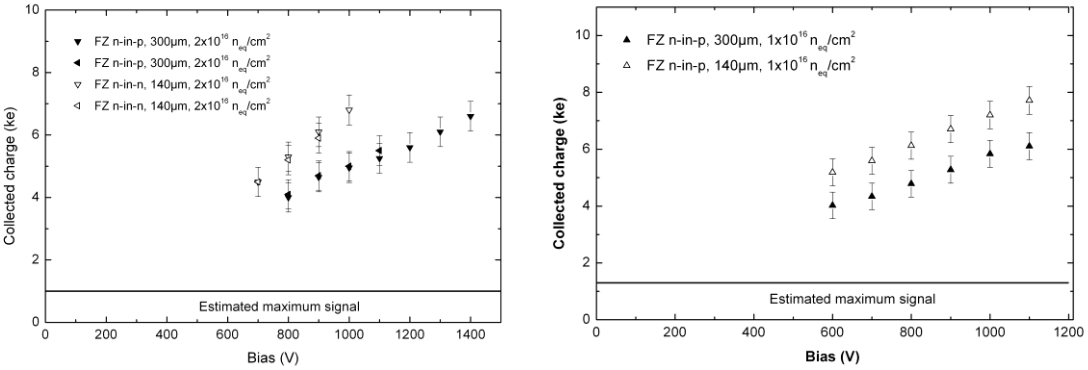

Figure 3: *CC(V) of 140 and 300 µm thick n-in-p microstrip detectors irradiated with protons to 1×10^{16} n_{eq} cm^{-2} (left) and with neutrons to 2×10^{16} n_{eq} cm^{-2} (right). The figure also shows the expected signal when the charge carrier trapping is considered.*

The charge collected by the thin devices goes up to about 25 ke$^-$, which is more than twice the charge ionised by a mip in the full volume of a non-irradiated 140 μm thick silicon detector, clearly indicating that charge multiplication is taking place.

Another important fact emerging from the measurements is the capability of the irradiated sensors to withstand bias voltages exceeding 1000V. The measurements here shown have been performed at -25°C to keep the I_R under control and avoid thermal runaway. The detectors were operated in stable conditions and continuously for several hours (up to a few days).

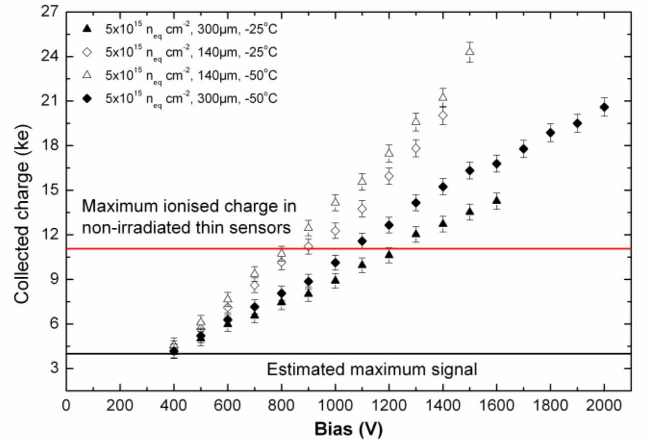

Figure 4: *CC(V) of proton irradiated n-in-p microstrip detectors (140 and 300 μm thick) after 5×10^{15} n$_{eq}$ cm^{-2}. The figure also shows the expected signal when the charge carrier trapping is considered. The charge collected by the thin device is almost a factor of two higher than the charge deposited by a mip in the full depleted bulk of a non-irradiated sensor. Two set of measurements have been taken with both detectors, at -25 and -50°C.*

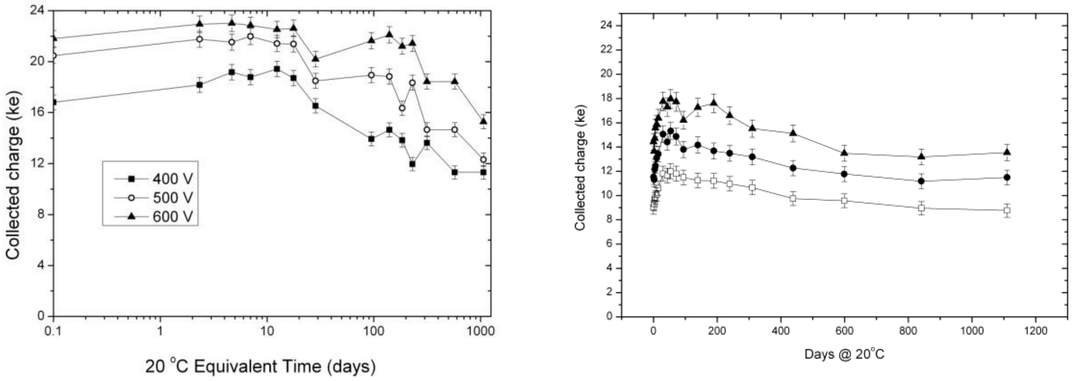

Figure 5: *Signal as a function of RT equivalent time of a p-in-n detector irradiated with reactor neutrons to 2×10^{14} n$_{eq}$ cm^{-2} (left) and a n-in-p detector to 1×10^{15} n$_{eq}$ cm^{-2} (right).*

Beside the need for reducing the reverse current, a possible improvement of the charge collection through changes of the carrier mobility and trapping centre occupancies could justify running the irradiated sensors at lower temperatures. Only a rather small difference is though found between the signal measured at -25 °C and -50°C (Fig. 4).

Annealing of the CC(V)

It could be assumed that the CC(V) follows closely the annealing of the full depletion voltage, with corrections coming from the annealing of the charge trapping probability that is reducing with time after irradiation [10]. But while these two aspects only depend on the irradiation dose and on the type of the silicon crystal, the annealing of the CC(V) strongly depends on the readout side. Figure 5 shows the changes of the CC(V) with time after irradiation for a p-in-n and a n-in-p sensors irradiated to 2×10^{14} n_{eq} cm^{-2} and 1×10^{15} n_{eq} cm^{-2} with reactor neutrons. To study the annealing behaviour over a few years at room temperature (RT=20^{o}C) equivalent time (t_{eq}), the sensors have been taken through controlled heating steps (from 30 minutes to two hours) at 60 or 80 ^{o}C, for an acceleration factor of about 540 and 7400 relatively to RT. The CC(V) of the p-in-n device measured at 500 and 600 volts is essentially stable (the maximum increase is below 5%) up to 20 days t_{eq}. Both bias voltages are above the expected value of V_{FD} (Fig. 1) that goes from just under 500V to about 320V over the same period of time. The signal at 400V shows an increase of about 17%, due to V_{FD} going from above to below this bias voltage. Although being fully depleted, a smaller charge is measured at 400V with respect to 600V, which is attributed the more intense charge trapping at the lower bias. After 30 RT equivalent days, the signal at 400V and 500V keeps degrading and about 30% of the charge measured at the end of the irradiation is lost after approximately 1000 days. There is some discrepancy with the expected behaviour, because V_{FD} becomes higher than 400V and 500V only after about 130 and 320 days of annealing, while the collected charge has already reduced. As expected, the signal measured at 600V degrades at a lower rate. At this voltage, the signal is practically stable for about one year, then it degrades to a loss of ~ 20% after 1000 days.

The n-in-p device shows instead a significant increase of the signal (up t0 30%) during 100 days, followed by a slow degradation to retrieve the same level measured at the end of the irradiation after about 1000 days (Fig. 5). The signal is more than 20% higher than its initial value during a time exceeding 300 equivalent days.

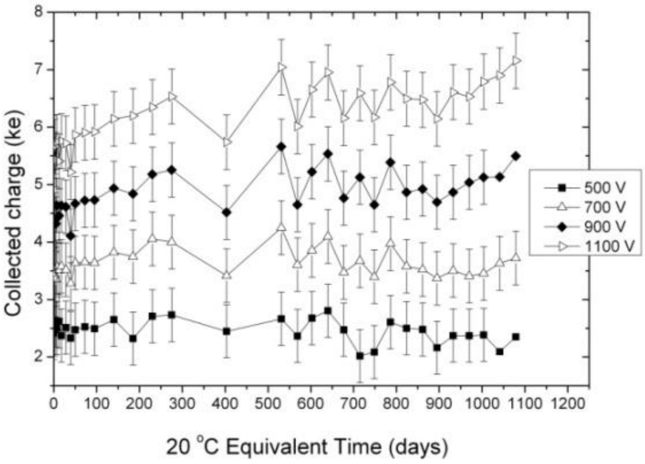

Figure 6: *Signal as a function of the equivalent annealing time for a n-in-p detector irradiated with 26MeV protons to* 1.5×10^{16} n_{eq} cm^{-2}.

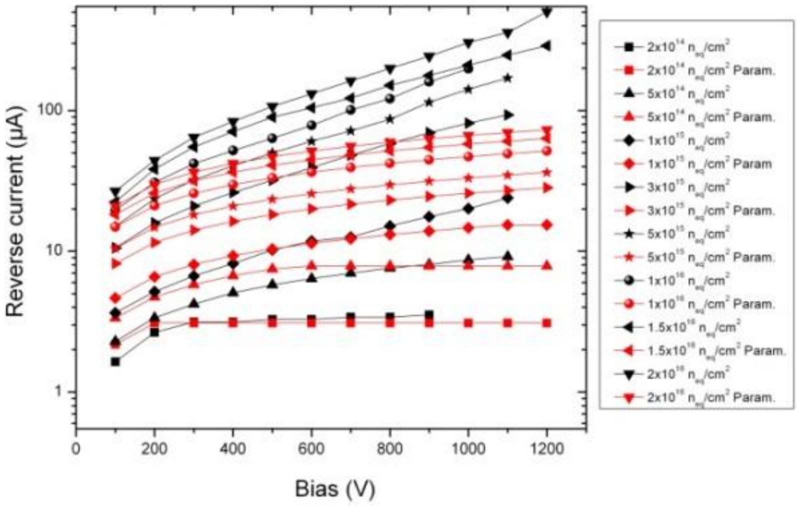

Figure 7: *Expected (red) and measured reverse current as a function of the reverse bias voltage (I-V) for silicon detector irradiated to different doses.*

After higher fluences of neutron irradiation the collected charge exhibits different annealing behaviours. Figure 6 shows the signal measured at four different reverse bias voltages (up to 1100V) for a microstrip sensor irradiated with 26MeV protons to 1.5×10^{16} n$_{eq}$ cm^{-2} as a function of RT equivalent time. The increase of the measured signal is much slower than in the case of the sensors irradiated to lower doses, but it is still higher that the initial value for at least 1100 days at 20^{o}C.

Changes of the reverse current with irradiation and annealing time

Using the accepted parameterisation it is possible to calculate the reverse current at any irradiation dose and temperature. This is based on measurements performed up to fluences of about 1×10^{15} n$_{eq}$ cm^{-2}. But at higher hadron doses, the reverse current does not follow the expected behaviour. Figure 7 shows the comparison of the calculated and measured reverse current as a function of the reverse bias voltage for silicon detectors irradiated to different doses. At the lower fluences the difference is relatively small, with the exception of the points above 800 V for the detector irradiated to 1×10^{15} n$_{eq}$ cm^{-2}. At larger doses the measured currents are considerably higher than the calculated ones. This could be due to the same charge multiplication mechanism that is assumed to enhance the signal after irradiation.

Also the annealing of the reverse current with time after irradiation does not follow the parameterisation used to fit the data at lower doses. Because the charge multiplication effect could depend on various parameters of the segmented implants and on the junction profile, a general parameterisation of the reverse current at higher doses for the irradiated silicon microstrip detectors might not be possible and direct measurements with a given type of sensors could be required. Nonetheless the general trend of a relatively fast decrease of the current with time after irradiation is verified. Figure 7 shows the annealing behaviour of the reverse current for detectors irradiated with neutrons to 1×10^{15} n$_{eq}$ cm^{-2} and with 26MeV protons to 1.5×10^{16} n$_{eq}$

cm^{-2} A significant decrease of I_R takes place already in the first 50 t_{eq} days, with a reduction of about 40%. The I_R keeps than decreasing with time at a slower rate.

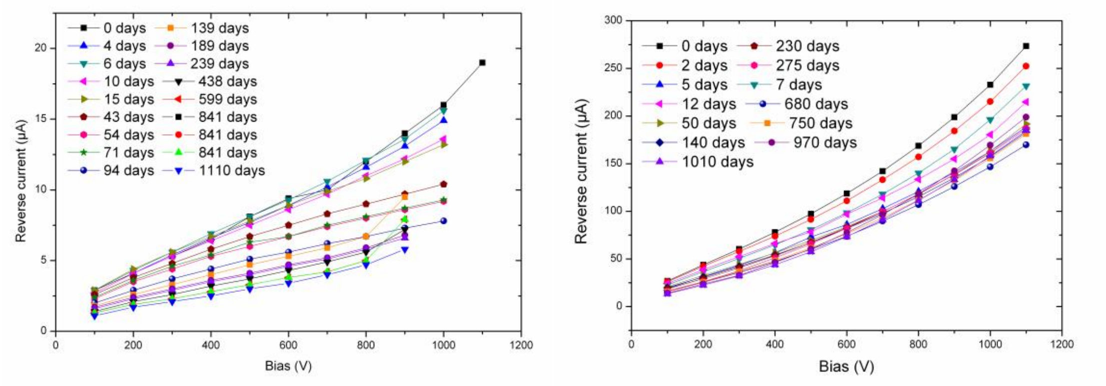

Figure 8: *Annealing of the reverse current for detectors irradiated with neutrons to 1×1^{15} n_{eq} cm^{-2} (left) and with protons to 1.5×1^{16} n_{eq} cm^{-2}). The various annealing times are in 20°C equivalent days (the study has been accelerated at 60 and 80°C).*

Implications for the operation scenarios in future super-colliders

We attempt here to give general recommendations for operating high irradiated silicon detectors for high energy physics applications. Issues like the signal over noise are not considered, although essential to assess the efficiency of the detectors, because of the dependence of the noise on the particular geometry. Figure 9 shows the degradation of the signal with hadron fluence at 500V and 900V.

These plots can be used to read the expected signal after the dose of interest and to evaluate the S/N for a specific electronics system. Remarkably, a signal of ~5000 electrons is still measured after $2x10^{16}$ n_{eq} cm^{-2}, sufficient to guarantee a tracking efficiency close to 100% with an electron noise charge of 500. The data refer to the signal before annealing: they are therefore the minimum collected charge after every dose. The measurements have been taken at operation temperatures between -15/-25 °C. After the highest doses, -25 °C is required for long term stable operation (this requirement can be relaxed for lower doses, where for example -15°C is sufficient for operating silicon sensors irradiated to 1x1015 neq cm-2). There is the possibility of increasing the signal by as much as 30% by means of controlled annealing outside of physics data taking periods. The most significant improvement is found with the sensor irradiated to $1x10^{15}$ n_{eq} cm^{-2} and the highly irradiated sensor shows a signal that does not degrade with time after irradiation. Due to the dependence of the signal recovery on the fluence further measurements are required to experimentally assess the improvement of the collected charge with annealing time after various doses. An undisputable advantage of the annealing is the reduction of the current of the devices with time after irradiation. Namely, it can be concluded that an annealing time of about 50 days at room temperature can reduce the reverse current by 40% for both the fluences shown (Fig. 8). In the absence of an accurate model for describing the current and its annealing for severely irradiated silicon detectors, data from direct measurements should be employed. Table 1 shows an example of the power dissipated per cm^2 by silicon detectors biased at 500V and 1000V and operated at -25°C after various fluences of hadron irradiation.

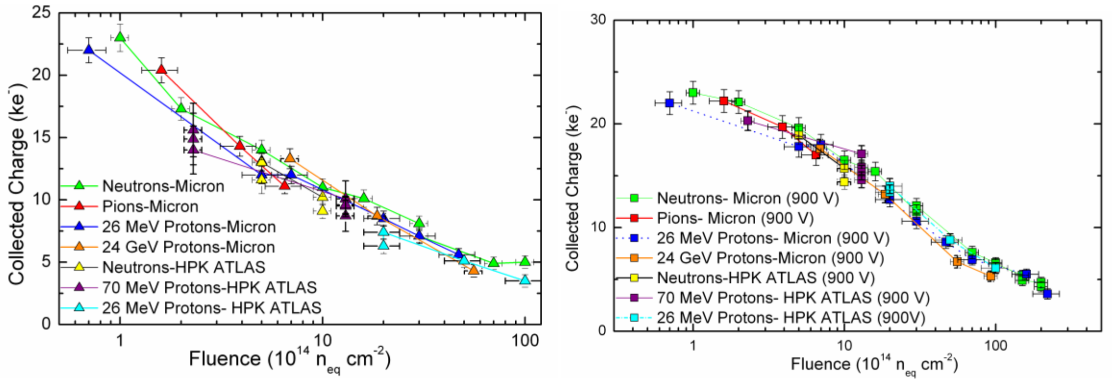

***Figure 9**. Degradation of the signal of n-in-p 300μm thick sensors irradiated with different hadrons as a function of fluence at 500V (left) and 900V (right).*

Conclusions

Planar silicon sensors exhibit higher than expected charge collection efficiency after irradiation, adequate for efficient tracking in all the layers of the upgraded experiments at the sLHC, provided that adequate cooling and power can be routed to the devices. Operating temperature of -25°C and bias voltages of up to 1000V are required for the innermost pixel layers, where hadron fluences of $2\text{x}10^{16}$ n_{eq} cm^{-2} can be expected. Although sub-zero temperatures are required during operations for preventing the thermal runaway of the reverse current and the consequent failure of the detectors, a noticeable improvement of the performance can be achieved by controlled annealing of the silicon sensors (e.g. at room temperature out of operation time).

It has also been shown that the accepted parameterisation of the changes of the electrical performance of the silicon sensors after hadron irradiation fails at high doses (above $1\text{x}10^{15}$ n_{eq} cm^{-2}). Above this dose the direct measurement of the signal and the reverse current should be used for anticipating the performance of the detector systems. Only the understanding of the mechanism responsible for the enhanced signal and increased reverse current in the highly dosed detectors (charge multiplication) will provide the model for describing the devices and accurately predict their performance without recurring to direct measurements.

Fluence (10^{15} n_{eq} cm^{-2})	***Power (mW/cm^2) at -25°C (no annealing)***		***Power (mW/cm^2) at -25°C (45d RT annealing)***		***Signal (ke)***
	500 V	***1000 V***	***500 V***	***1000 V***	***1000 V***
5	24	65	14.4	39	> 10
10	30.5	100	18.3	60	> 7
15	46.5	115	27.9	69	> 6
20	53.5	150	32.1	90	> 4

***Table 1:** Power dissipation of silicon detectors biased at 500V and 1000V and operated at -25°C after severe fluences of hadron irradiation.*

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