The Compact Muon Solenoid Experiment

CMS Note

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The performance of irradiated CMS silicon micro-strip detector modules

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Abstract

The central tracking system of the Compact Muon Solenoid (CMS) experiment will be entirely built in silicon technology. The majority of the CMS tracker consists of silicon micro-strip detectors which have to be operated in the harsh radiation environment of the Large Hadron Collider (LHC) over a period of ten years. The expected equivalent fluences range from a low of $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ at the outermost layers of the tracker, to a high of $1.6 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ at the layers closest to the interaction region. In this paper, results from studies of irradiated CMS silicon strip detector modules are presented.

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1 Introduction

The central tracking system of the Compact Muon Solenoid (CMS) experiment will be entirely built in silicon technology. The main part consists of silicon micro-strip detectors which have to endure the harsh environment of the Large Hadron Collider (LHC), a proton-proton collider with a centre of mass energy of $\sqrt{s} = 14$ TeV.

The silicon strip tracker is divided into four subsystems. The four innermost layers arranged cylindrically around the beam line make up the tracker inner barrel (TIB). These are followed by the six cylindrical layers of the tracker outer barrel (TOB). On either side of the TIB in the forward region, three disks with three layers of modules arranged in rings perpendicular to the beam line form the tracker inner disc (TID). The tracker end-cap (TEC) consists of nine discs in each forward direction. Discs are distinguished by the number of populated rings of modules that they contain. The number of rings per disc decreases with increasing distance from the interaction region (fig. 1).

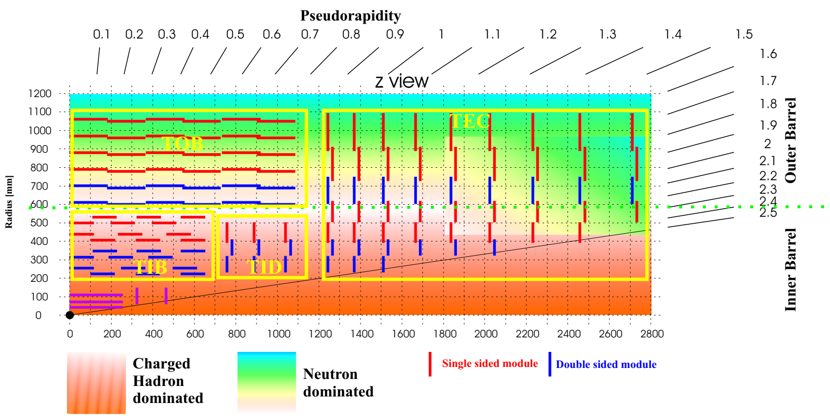

Figure 1: *Longitudinal section of one quadrant of the silicon strip tracker, single sided modules are indicated by red lines while "double sided" modules (made up of two single sided modules mounted back to back) are indicated by blue lines [1]. The expected fluences and the areas where charged particles or neutrons dominate, are also indicated*

The high collision rates of the 7 TeV proton beams at the LHC create a harsh radiation environment for the CMS silicon strip tracker. This has been taken into account in the design and construction of the detector, as well as in the selection of the material used in the detector. For example, to cope with the high radiation level expected in the inner layers the sensors have a thickness $320\,\mu$m while in the outer layers, where the conditions are less severe, sensors have thickness of $500\,\mu$m. The latter allows one to build larger detector modules with longer strips for which the increased noise is compensated by the increased signal generated in the additional sensor thickness.

In the inner part of the tracker the radiation environment is dominated by secondary particles, mainly charged hadrons, produced in the pp collisions. In the outer part of the tracker neutrons scattering off of the surrounding electromagnetic calorimeter start to dominate (fig.1). The maximum expected fluences are approximately for the TIB and TID $1.6 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ and $0.5 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ for TEC and TOB [2, 3]. Due to uncertainties in the expected fluences it is recommended that one applies a safety factor of 1.5 for the TIB and TID, and 2 for the TEC and TOB fluence for irradiation studies and qualification of the detectors [3].

2 The Irradiation Facilities

The irradiation qualification of CMS silicon strip detector modules was performed with both protons and neutrons. The neutron irradiation was performed at the Louvain-la-Neuve isochronous cyclotron. To reach the expected LHC fluences within a reasonable time scale, a neutron beam is created by steering a high intensity 50 MeV deuteron beam, with a beam current of $10\,\mu$A, on a beryllium target. The resulting neutrons have a spectrum with an average energy of 20 MeV. A hardness factor of $\kappa \approx 1.95$ was used to calculate the equivalent fluence for 1 MeV neutrons [4].

For the proton irradiation the compact cyclotron at the Forschungszentrum Karlsruhe was used. It provides 19 to 40 MeV protons with a beam current of up to $100\,\mu$A and a beam spot diameter of 1 cm. The hardness factor for the 26 MeV protons of $\kappa \approx 1.85$ was taken into account for calculating the equivalent fluences. Figure 2 shows the Karlsruhe irradiation facility. The structures to be irradiated are placed in a thermally insulated box, which can be cooled during irradiation by flushing the box with cold nitrogen gas. The box is installed on an x-y stage in front of the beam pipe, enabling one to scan an area of $400 \times 200\,\mathrm{mm}^2$ [5].

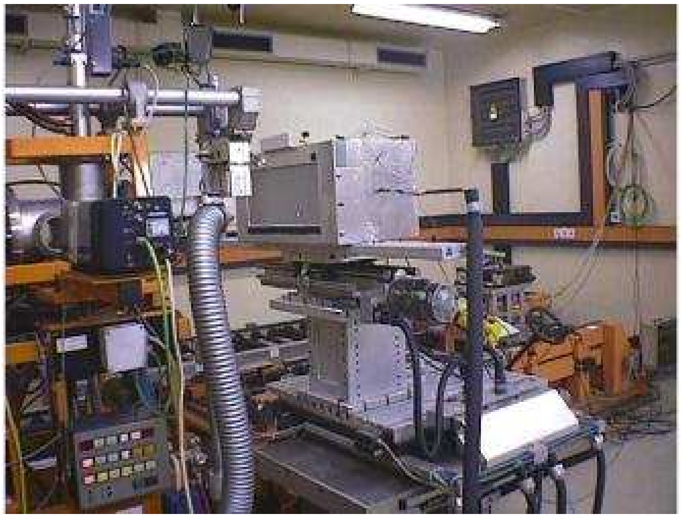

Figure 2: *The proton irradiation facility at the compact cyclotron in the Forschungszentrum Karlsruhe. The beam line enters from the left. The beam spot diameter is* $1\,\mathrm{cm}$*. An insulated box hosts the structures to be irradiated. The box is placed on an x-y stage in front of the beam line, allowing the beam to access a total area of* $400 \times 200\,mm^2$*. During irradiation the box is flushed with cold nitrogen gas to prevent annealing due to heating of the structures and to be close to the operating condition at the LHC [5]*

3 Results on the Hybrid Irradiation

To check the radiation hardness of silicon strip detector modules it is important to ensure that the front-end electronics directly connected to the silicon strip sensor are radiation hard. Therefore, bare front-end hybrids designed for CMS [6] were irradiated to the maximum fluence expected for ten years of operation at the LHC, which includes a safety factor of 1.5 [2, 3]. To simulate actual LHC operating conditions as closely as possible, the front-end hybrid was powered, initialised with the standard settings [7], supplied with clock signal and triggered at a rate of $50\,\mathrm{kHz}$ during irradiation [8].

The front-end hybrid was qualified before and after the irradiation, both at room temperature and at the nominal operating temperature of $-10°\mathrm{C}$. The qualification procedure requires an optical inspection to detect mishandling such as touched wire bonds, discolouration or loss of adhesive joints resulting from irradiation. In the next step the front-end hybrid is tested electrically by connecting it to the test-station, checking I2C communication, measuring pedestals and noise, and checking calibration data and the functionality of all pipeline cells. The readout of noise, pedestals and calibration signals was performed in all modes (peak and deconvolution), with and without the inverter stage and calibration unit on. This procedure allows one to determine the source of possible failures.

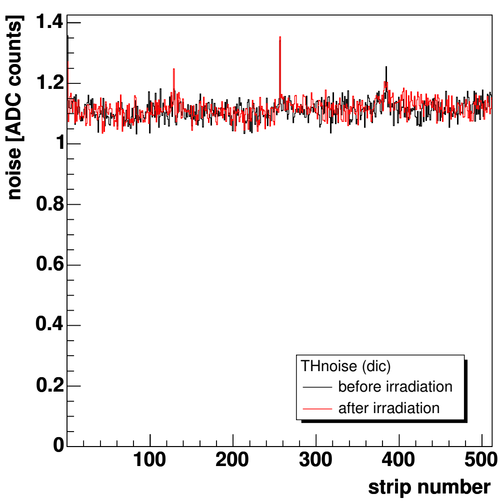

Figure 3: *Common mode corrected noise for each strip before and after irradiation in deconvolution readout mode with inverter stage and calibration unit switched on. The distribution indicates no change after irradiation*

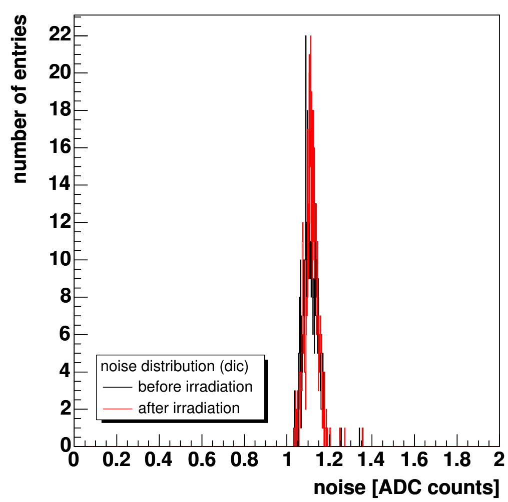

Figure 4: *Common mode corrected noise distributions before and after irradiation in deconvolution readout mode with inverter stage and calibration unit switched on. The difference in the mean values of the distributions is below* 1%

Figure 3 shows the noise for each channel, and figure 4 shows the noise distribution for operation of a hybrid, prior to connection to sensors, in deconvolution mode. Both graphs indicate that the noise behaviour of the APV readout does not change due to radiation. The shift in the mean noise is less than 1% as seen in figure 4. Figure 5 shows the calibration pulse shape in peak and deconvolution mode before and after irradiation. The amplitude of the calibration signal increased after irradiation which indicates an accumulation of charge in the oxide-layer of the n-mos transistors responsible for the adjustment of the calibration amplitude. The study of the front-end hybrid shows that the readout electronics remain fully operational after irradiation and hence will likely survive the harsh radiation environment at the LHC.

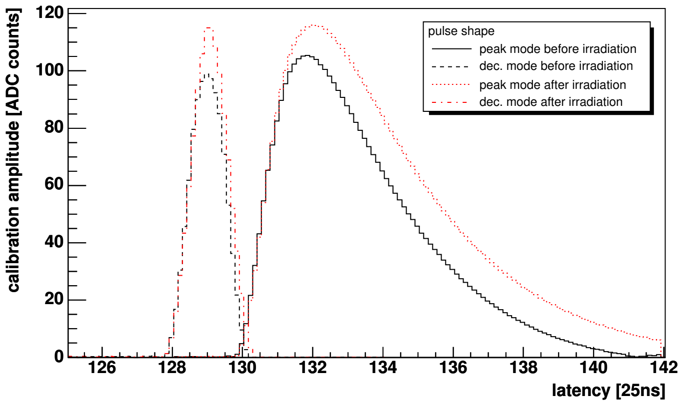

Figure 5: *Calibration pulse shapes in peak and deconvolution mode before and after irradiation. The calibration pulse shape is obtained by varying the time between the calibration trigger and the readout trigger to the APV chip*

4 Results on the Module Irradiation

After having shown that front-end hybrids are radiation hard, complete silicon strip modules were studied for their radiation hardness. Therefore several TOB modules were irradiated with protons to fluences ranging from $0.1 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ to $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. Only one module was irradiated with neutrons with fluence varying in the range $1.0 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ to $1.2 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. The variation in the fluence is due to the profile of the neutron beam and constraints associated with the positioning of the detector module in the irradiation setup [9]. Figure 6 gives an impression of the size of the module used in these irradiation studies.

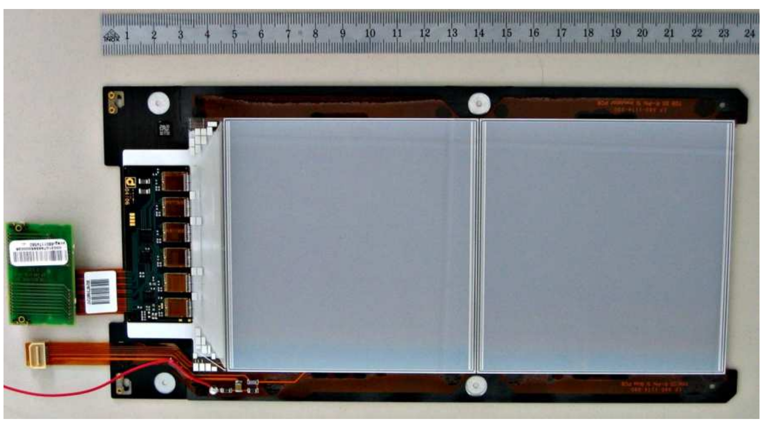

Figure 6: *A silicon strip detector module for the CMS outer barrel geometry. The module consists of the readout hybrid, which hosts the APV chips, and two silicon sensors. Each sensor has a length of* 94.4 *mm and a width of* 96.4 *mm. All components are mounted on a carbon fibre frame*

The aim of the irradiation study is to qualify the robustness of the detector design, to prove the radiation hardness of the complete system and to show that the detector can be operated for 10 years at LHC. Therefore the annealing behaviour of the depletion voltage, the evolution of the leakage current during the annealing steps and the signal to noise ratio (SNR) have been studied.

All annealing steps were performed at $60\,^{\circ}\mathrm{C}$ in a controlled oven and afterwards the modules were stored at room temperature for at least two hours. Between the measurements and the individual annealing steps the modules were stored in a refrigerator at $\approx -20\,^{\circ}\mathrm{C}$ to prevent any further annealing process. The measurements were performed at about $-15\,^{\circ}\mathrm{C}$ to keep the leakage currents below the current limit of the high voltage supply (1 mA) and to be as close as possible to the operating conditions of the LHC.

4.1 Depletion Voltage

The voltage at full depletion of the sensors in a module can be determined via a measurement of the capacitance as a function of bias voltage. The bias voltage was applied by bypassing the module's filtering capacitors and using a micro-manipulation probe to make the ground connection to the bias ring. To extract the full depletion voltage, the inverse of the squared capacitance is plotted versus the bias voltage (fig. 7). The point of intersection of the two linear regressions defines the full depletion voltage.

It is important to understand the behaviour of the full depletion voltage for the operation of the central tracker over a period of ten years at LHC. During this time the data taking runs will be interrupted by machine development and maintenance periods when the detector is warmed up to room temperature. During these periods the annealing processes are accelerated compared to the nominal operating temperature of $\approx -10°$C. On the one hand, care must be taken to avoid reverse annealing. On the other hand, it will be vital to the CMS tracker to fully anneal the defects accumulated during operation periods in order to keep the full depletion as low as possible.

Figure 8 shows the annealing of the full depletion voltage for a CMS outer barrel module irradiated with protons to an equivalent fluence of $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. The beneficial annealing process, starting directly after irradiation, causes a decrease of the full depletion voltage from 350 V to 240 V. The full depletion voltage reaches its minimum after ≈ 80 min at $60\,°$C, corresponding to approximately ten days at room temperature. Afterwards the reverse annealing process dominates with a resulting increase of the full depletion voltage up to more than 800 V after several days at $60\,°$C.

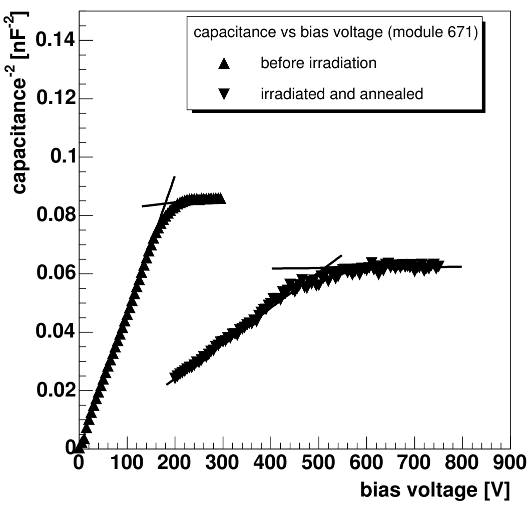

Figure 7: *Determination of the depletion voltage from the inverse squared capacitance plotted versus the bias voltage before and after irradiation (up to* $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$*). The measurement after irradiation is shown for* 17 *hours annealing at* $60\,°C$*, which is far into the regime of reverse annealing*

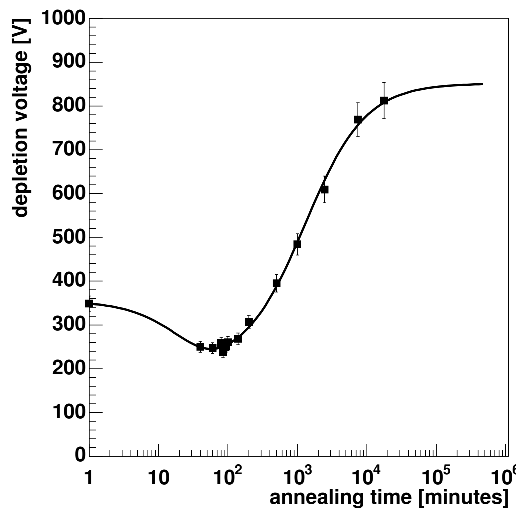

Figure 8: *Annealing of the depletion voltage for an outer barrel module irradiated with protons up to* $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$*. The "Hamburg model" (curve) is fitted to the data points [10]. The depletion voltage reaches a minimum near* 80 *min for an annealing temperature of* $60\,°C$*, which corresponds to* ≈ 10 *days at room temperature*

In Figure 9 the full depletion voltage versus the accumulated fluence for several detector module geometries is shown. Each point represents a detector module annealed for 80 min at $60\,°$C. The curve shows the expected values for the "Hamburg Model" [10]. On the basis of this figure one can estimate the expected depletion voltage during the operation at LHC.

4.2 Leakage Current

Another important parameter for the operation of silicon strip detectors is the leakage current. On the one hand the leakage current directly contributes to the detector noise, degrading the signal to noise ratio. On the other hand, it affects the power consumption, thereby defining the specification of the power supplies. Furthermore, the power consumption occurs mostly as a result of energy being dissipated as heat in the silicon sensors and has to be taken

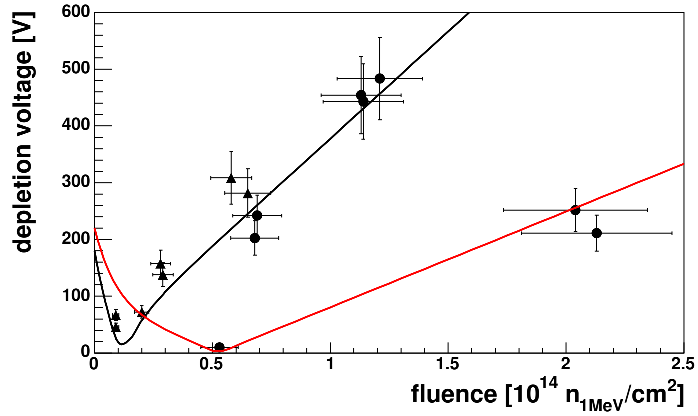

Figure 9: *Variation of depletion voltage with accumulated fluence. Data are compared to calculations for an annealing time of* 80 *min and an annealing temperature of* 60 °*C at each fluence step, for* 500 μ*m (upper curve) and* 320 μ*m (lower curve) thick silicon sensors. As full depletion voltage before irradiation the average of the corresponding modules were chosen*

into account in the design of the cooling plants to be used.

Figure 10 shows the increase of the current density with accumulated fluence for full silicon strip detector modules. Data points are the values of current density measured after annealing for 80 min at 60 °C and scaled to 20 °C. The slope of this graph is the current related damage rate α, obtained from the fit to be $(3.79{\pm}0.27){\times}10^{-17}\ A/cm$. The current related damage rate is defined as the current increase per sensor volume and equivalent neutron fluence. The measured value is in good agreement with data in literature [10] measured on diodes and test structures. Figure 11 shows the annealing behaviour of the leakage current for three modules. The leakage currents are scaled to -10 °C in this case.

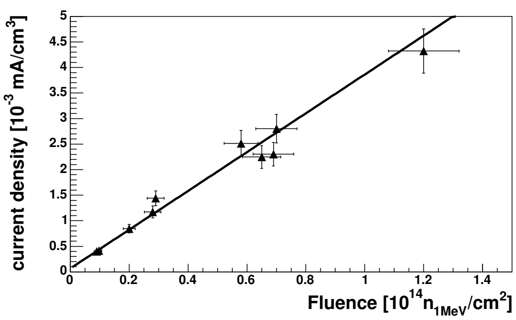

Figure 10: *Fluence dependence of current density for a full silicon strip detector module. The current was measured after annealing for* 80 *min at* 60 °*C. The slope of this graph is the current related damage rate* α*, which is obtained here by linear regression to* $(3.79 \pm 0.27) \times 10^{-17}$ *A/cm*

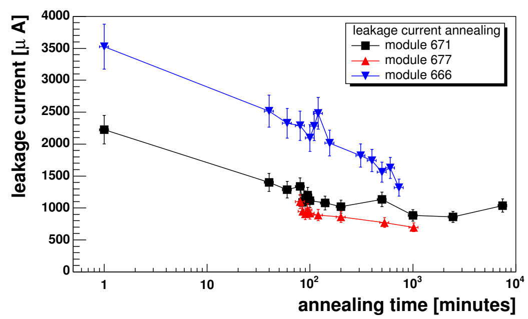

Figure 11: *Annealing behaviour of the leakage current at* 60 °*C for the three modules. The leakage currents are scaled to* -10 °*C, the operating temperature of the central tracker. Module 666 was irradiated with neutrons to* $1.2 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ *and module 671 and 677 with protons to* $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$

4.3 Signal to Noise Ratio

The signal to noise ratio (SNR) is an important variable used to understand the detector's response and it is an important criterion for the qualification of irradiated detector modules. Most of the measurements were performed using a ^{90}Sr source. The SNR obtained from cosmics and source measurements are comparable. An advantage of the radioactive source however is the much shorter exposure time that is required to make an accurate SNR measurement. A detailed study of the behaviour of the SNR for non-irradiated CMS silicon strip modules can be found in [11].

To obtain the optimum SNR, the delay time between the trigger signal generated by the particles coincidence and the trigger sent to the readout electronics was adjusted after each annealing step if necessary. For each voltage step about 5000 events were recorded and the resulting energy loss distribution was analysed by fitting the data to a convolution of a Landau distribution and a Gaussian distribution (fig. 12).

The SNR is expected to increase with voltage below full depletion since the extend of the space charge region

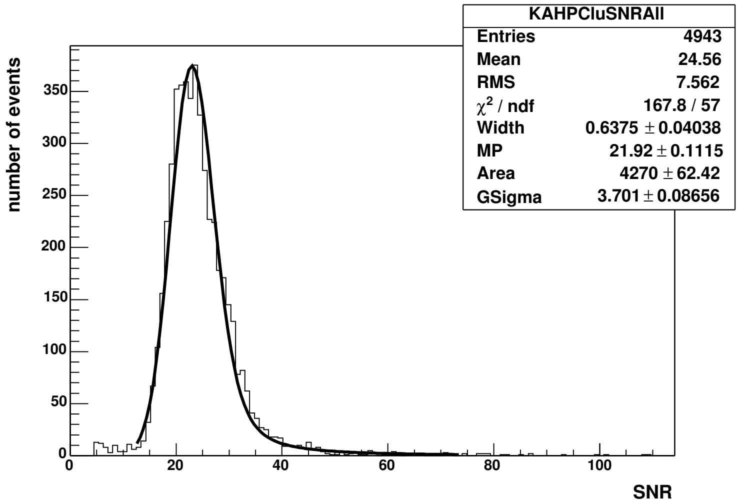

Figure 12: *Signal to noise distribution for module 671 at a bias voltage of* $400\,\mathrm{V}$*, fitted by a Landau distribution convoluted with a Gaussian distribution. The module was irradiated to* $0.7 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ *and annealed for* 80 *min at* $60\,^{\circ}C$

scales with the square root of the bias voltage. When full depletion of the detector is reached the SNR saturates in a plateau. However a small increase with bias voltage is still observed, which is due to the increase in the electric field strength and therefore an increase in the drift velocity. This means that more charge is collected during the sampling time of the preamplifier.

In figure 13 and 14 the SNR versus bias voltage for module 677 in peak and deconvolution modes is plotted. Before and after irradiation the module shows the expected behaviour. The saturation of the SNR starts at a bias voltage which is about a factor of 1.4 larger than the measured depletion voltage. This is in good agreement with previous measurements [11] and test beam results [12].

Figure 15 and 16 summarise the measured SNR at the nominal operation voltages for all modules investigated. The SNR decreases from ≈ 23 (35) to ≈ 15 (21) in deconvolution mode (peak mode) for modules with $500\,\mu$m thick sensors and from ≈ 18 (24) to ≈ 13 (18) in deconvolution mode (peak mode) for modules with $320\,\mu$m thick sensors. The SNR measurement shows that the CMS silicon-strip detector modules continue to operate with a sufficient safety margin even at higher fluences.

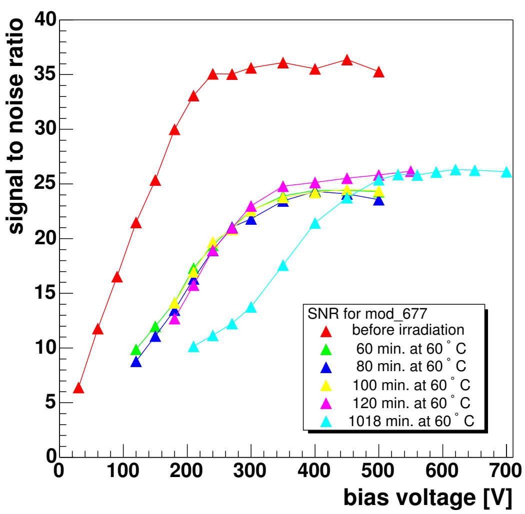

Figure 13: *Signal to noise ratio for various annealing steps on TOB module 677 in peak mode inverter off*

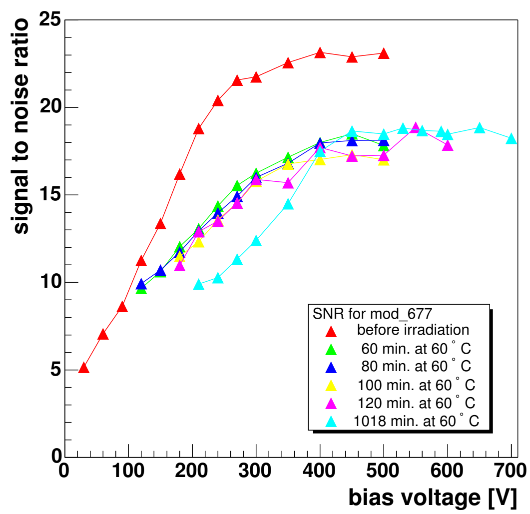

Figure 14: *Signal to noise ratio for various annealing steps on TOB module 677 in deconvolution mode inverter off*

5 Conclusion

The study presented here demonstrates the radiation hardness of the CMS silicon strip modules and their readout electronics. Leakage currents and full depletion voltages were measured for various fluences. The study finds that the parametrisation developed for small test-structures and diodes [10] also applies for large and complex

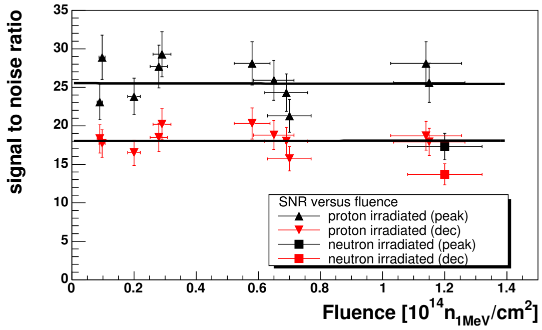

Figure 15: *Signal to noise versus fluence for modules built of* 500 μ*m thick sensor*

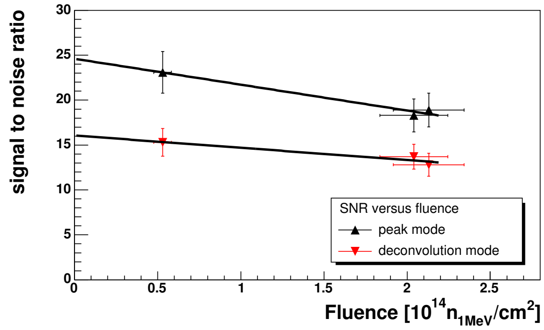

Figure 16: *Signal to noise versus fluence for modules built of* 320 μ*m thick sensor*

structures such as CMS silicon strip sensors. Full depletion voltage and leakage current at the end of the operation period of LHC are important input parameters for the design of the power supplies and the cooling system. The signal to noise measurements show that there is sufficient margin for the operation of the central tracker to allow for the possibility that the accumulated fluence turns out to be higher than expected.

6 Acknowledgement

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