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Radiation tolerance of the readout chip for the phase I upgrade of the CMS pixel detector

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Abstract

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Radiation tolerance of the readout chip for the Phase I upgrade of the CMS pixel detector

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KEYWORDS: CMS; pixel; upgrade; radiation; readout chip.

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1. The Phase I upgrade of the CMS pixel detector

The Compact Muon Solenoid (CMS) experiment is one of the two general purpose detectors at the Large Hadron Collider (LHC) at CERN. It is composed of layers of different sub-detectors, each of them measuring a certain property of elementary particles, which are produced in proton-proton collisions at the center of the experiment [1]. The innermost sub-detector is a position sensitive silicon pixel detector, which measures the trajectories of charged particles at radii between 4.4 and 10.2 cm from the interaction point [2]. It has about 66 million readout channels and consists of several layers of sensitive material, three cylindrical layers in the barrel part and two disk-like endcaps on each side providing a wide angular coverage up to a pseudo-rapidity of $\eta = 2.5$. The pseudo-rapidity is a function of the polar angle θ , measured against the beam axis and defined as $\eta = -\ln \tan \theta/2$. With a pixel size of $100 \times 150 \mu\text{m}^2$ the detector achieves a spatial resolution of about $10 \mu\text{m}$ in the direction perpendicular to the beams and approximately $24 \mu\text{m}$ in the direction parallel to the beam pipe. An excellent spatial resolution is crucial for a wide range of physics analyses that rely on tracking and on the resolution of primary and secondary vertices of the produced particles. Governed by the LHC bunch crossing frequency, the pixel detector is operated at a frequency of 40 MHz and it has to store hit information during the latency of the CMS level-1 (L1) trigger for about $3.9 \mu\text{s}$.

The present CMS pixel detector has been operated during the first run of the LHC between 2010 and 2012 and has resumed operation in May 2015 after Long Shutdown 1 of the LHC, now recording proton-proton collisions at a center-of-mass energy of 13 TeV. Despite of its excellent

performance it is foreseen to replace the pixel detector during an extended year-end technical stop of the LHC in winter 2016/2017 since the design luminosity of the detector of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will be exceeded by then, leading to unacceptable tracking inefficiencies. Moreover, the detector suffers from radiation damage causing a loss of charge collection efficiency [3]. The goal of the so-called Phase I upgrade of the pixel detector is to maintain or even improve the performance of the detector under harsher conditions with instantaneous luminosities up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

To this end a new detector with improved components and additional features will be installed [4]. A fourth layer in the barrel and an additional disk on each side will provide more measuring points and thus an improved tracking performance. These additional layers almost double the number of channels of the detector. By moving the innermost layer closer to the interaction point to then 3.0 cm, a better resolution of secondary vertices, e.g., from the decay of short-lived b-mesons, will be achieved. Furthermore, the installation of a cooling system based on two-phase CO_2 coolant, instead of the presently used heavier liquid mono-phase C_6F_{14} , guarantees high cooling efficiency and reduces the amount of material in the detector. Moving service electronics out of the tracking volume also helps to minimize multiple scattering of particles and therefore improves the tracking performance. Supply voltages for the detector will be provided by a new powering scheme based on DC-DC converters [5].

In the context of this paper, the most important change is the transition from analog to digital readout, which requires a new readout chip (ROC) with increased readout speed, allowing to operate the detector at higher instantaneous luminosities.

2. The readout chip

The new digital readout chip *PSI46digV2* for the Phase I upgrade is an advancement of the analog ROC employed in the present detector. Both versions are manufactured in 250 nm CMOS technology and consist of 4160 pixels arranged in 26 double columns (DCol) and 80 rows. At the periphery outside of the pixel array, data and time stamp buffers for each DCol as well as other auxiliary components are located. For the new ROC an 8-bit analog-to-digital (ADC) converter for on-chip digitization of the pulse height information has been included in the design.

The ROC is bump-bonded to a segmented silicon sensor, where charged particles generate electron-hole pairs in the depleted volume. The thereby generated charge is collected with an electric field applied to the sensor and read out with the pixel-unit-cells (PUC) of the ROC. In the PUC the charge is amplified and shaped before it is compared to an adjustable threshold. This threshold allows to separate signals originating from particle hits from noise and is therefore important for zero-suppression of the readout of the detector — a feature that is crucial to keep the transmitted data volume manageable given the vast amount of channels and the bunch crossing frequency of 40 MHz. If a signal exceeds the pixel's threshold it is sent to the buffers in the DCol periphery where it waits for L1 trigger validation. If validated, the hit information is read out from the buffer and used for higher level trigger decisions and finally for the event reconstruction. Not validated hits are cleared after the trigger latency. The ROC is controlled by 18 digital-to-analog (DAC) converters and registers, some of which have to be optimized for each ROC individually in order to achieve optimal performance of the detector. For test and calibration purposes, test pulses with variable amplitude can be injected into the PUC.

With the increased luminosity of the LHC, the new digital ROC faces several challenges. Most prominently the hit finding efficiency has to be kept at a high level despite of the increase in occupancy. The occupancy increases as a consequence of the higher luminosity, increased cross-sections at higher center-of-mass energy of the colliding protons, and, in case of the innermost layer, because of the smaller distance to the interaction point. In order to maintain the performance, both hit and time stamp buffers of the DCols have been increased to prevent buffer overflow [6]. Additionally, a new readout buffer has been introduced to reduce dead times of the DCol interfaces during the readout of other ROCs in the same detector module. The readout of validated hits from the new buffer is then initiated by the passage of an external token. The transition from analog to digital readout is mainly motivated by the doubling of the number of readout channels in combination with constraints on the number of readout links. The required increase of bandwidth is achieved by employing 160 Mbit/s digital readout instead of the 40 MHz analog readout of the present detector. In terms of longevity of the detector, a lower pixel threshold of about 1500 – 2000 electrons is beneficial since it allows to read out smaller charges, which is especially important towards the end of the lifetime of the detector, when the charge collection efficiency of the sensor has been degraded by radiation damage. However, a lower threshold also requires to minimize cross-talk and timewalk effects of the ROC.

Even though the digital ROC is derived from an existing front-end, the new design contains multiple new features and circuits which need to be tested thoroughly in order to guarantee the expected performance. These tests comprise electrical measurements, beam tests to mimic realistic operation environments, and irradiation studies to ensure sufficient longevity of the ROC.

This paper summarizes a study on the radiation tolerance of the ROC that will be used for layer 2 – 4 and in the forward part of the new detector. For the innermost layer in the barrel part a dedicated ROC, designed for even higher occupancies close to the interaction point, will be used.

3. Irradiation and test setups

The upgraded CMS pixel detector is foreseen to be operated until Long Shutdown 3 of the LHC, currently scheduled to start in 2024. It is estimated that the experiment will collect about 300 – 500 fb⁻¹ of proton-proton collisions by then. For this integrated luminosity, a hadron fluence up to $\Phi \approx 3 \times 10^{15}$ n_{eq}/cm² [4] is expected for the innermost layer of the detector, leading to a significant amount of energy absorbed in the front-end electronics. While the sensor performance mainly degrades with increasing silicon bulk damage, the readout electronics are affected by energy deposition in the gate-oxide layers of field effect transistors, which in turn causes transistor thresholds to shift and reduces the charge carrier mobility in the channel. For that reason the total ionizing dose (TID) absorbed by the ROC is the quantity of interest when assessing its radiation tolerance. The purpose of the presented study is to test the longevity of the ROC in the harsh radiative environment at the center of the CMS experiment and to ensure good performance throughout its foreseen lifetime. This implies to test if the available DAC ranges and supply voltages are sufficient and to evaluate which chip properties change with irradiation and by how much.

For this purpose samples of the ROC have been irradiated with 23 MeV protons at ZAG, Germany [7]. Given the stopping power of 18.1 MeV cm²/g [8], the proton fluences have been chosen such that the samples absorb doses corresponding to different scenarios. A dose of 0.6 MGy

Table 1. Target and measured doses (single chip module samples / bare ROC samples), corresponding fluences expressed in protons and 1 MeV neutron equivalents, and the number of tested samples (single chip module samples / bare ROC samples).

dose (MGy)		fluence		# of samples
target	measured	(protons/cm ²)	(n _{eq} /cm ²)	
0.6	0.5/0.6	0.2×10^{15}	0.4×10^{15}	3/6
1.2	1.1/1.5	0.4×10^{15}	0.8×10^{15}	4/6
2.4	2.2/—	0.8×10^{15}	1.6×10^{15}	3/—
4.8	4.2/—	1.6×10^{15}	3.2×10^{15}	3/—

serves as an upper limit for the expected dose for layer 2 of the detector for 500 fb^{-1} , i.e., this dose point is the maximum expected dose this version of the ROC will be exposed to. A higher irradiation level of 1.2 MGy is the estimated TID for layer 1 of the detector and was tested in order to project the performance of the layer 1 ROC, since several of its components will be inherited from the ROC under study. Even higher irradiation doses of 2.4 and 4.8 MGy have been studied to explore the limits of the current chip design in 250 nm CMOS technology in terms of TID. The irradiation facility delivers a dose rate of about 130 kGy/min and quotes a 20% uncertainty on the measured dose. Table 1 summarizes the target doses together with the corresponding particle fluences as well as the actual dose as measured by dosimetry. In the following the measured dose will be quoted. For the conversion between the fluence expressed in protons and 1 MeV neutron equivalents a hardness factor of 2 is assumed. The table also gives an overview of how many samples have been used in this study. In order to prevent annealing, the samples are kept at low temperatures of about -25°C during irradiation and storage.

Two types of samples have been irradiated, bare ROCs and ROCs bump bonded to a silicon sensor. These so-called single chip modules (SCM) can be used to study the performance of the ROC under high rates of external particles, while bare ROC samples offer the possibility to assess ROC performances without the additional input capacity of the sensor.

All samples have been qualified both before and after irradiation in order to evaluate possible irradiation induced changes in optimal DAC settings and important performance parameters. For this qualification two test setups have been used, one of them dedicated to electrical tests and the other to tests and calibrations with X-radiation. In both test setups the samples are tested under controlled temperature and humidity. In order to test the samples under realistic conditions and in order to minimize leakage currents in the sensors of the SCM samples, all tests have been performed at a temperature of -20°C . The samples are mounted on a PCB and connected to a test board, which emulates the back-end system of the CMS experiment. It provides clock and trigger information to the samples and is used to program DACs and registers on the ROC. An FPGA on the board allows to execute fast test sequences and to sample the data received from the device under test. The data is then sent via USB to a standard computer running the readout software.

4. Results

This section presents selected results from the irradiation study performed with the final version of the digital pixel ROC which will be used in the barrel layers 2 – 4 and in the endcaps of the detector. The focus is set on chip properties which are most relevant for operation or where irradiation induced effects have been observed.

4.1 Band gap reference voltage

Figure 1. Absolute value of the band gap reference voltage as function of dose.

Figure 2. Analog current as a function of the regulator setting. The dose dependent saturation is due to insufficient regulator drop out voltages.

The ROC contains a bandgap voltage reference to create a fixed voltage independent of supply voltages and temperature. It serves as a reference for all DACs and ADCs on the ROC and therefore greatly influences their outputs and thereby, e.g., the optimal DAC parameter settings of the ROC. In order to evaluate irradiation induced shifts of the voltage, it has been measured before and after irradiation on a dedicated probe pad at the periphery of the ROC. Figure 1 shows the mean and the standard deviation of the voltage measured for different samples as a function of dose. It can be seen that the reference voltage increases by 11% for the expected lifetime TID of the ROC with respect to the value measured before irradiation. For higher doses the shift becomes slower and reaches an increase of about 14% at a dose of 4.2 MGy. Since the output of DACs, e.g., test pulse amplitudes, are dependent on the reference voltage, this data has been used for subsequent measurements to correct band gap related shifts of DAC settings after irradiation.

4.2 Analog current and test pulse readout

Before a sample can be operated it is required to set the supply current of the analog part of the pixel unit cells to a working point of about 24 mA. The corresponding current regulator is controlled by the *Vana* DAC setting. As shown in Figure 2, analog currents between 5 and 50 mA can be set with the regulator for a default supply voltage of 1.6 V, both before irradiation and also

Figure 3. Maximum analog current as function of dose for a supply voltage of 1.6 V and for increased voltages after heavy irradiation.

Figure 4. Preamplifier noise measured with SCM samples for different doses. The noise stays well below 200 electrons up to 4.2 MGy.

after the samples received a TID of 0.5 MGy. In the latter case the change in slope for low DAC settings is caused by the shift of the reference voltage as described in Section 4.1. For higher TID a saturation of the analog current at a dose dependent level can be observed, leading to a decrease of the maximum analog current that can be set as depicted in Figure 3. Since the analog current can be set with a sufficient margin above the working point for doses up to 1.1 MGy, this is not considered problematic for the layer 1 ROC. For heavier irradiation however, the analog current eventually drops below the working point, owing to increased regulator dropout voltages. This explanation is motivated by the observation that the saturation level of the current increases for higher supply voltages. As shown in Figure 3 heavily irradiated ROCs have to be operated with a supply voltage elevated by 100 – 200 mV.

Since the current changes with the corresponding DAC setting, Figure 2 also implicitly shows that all samples could be programmed after irradiation. This is a prerequisite for successful operation of the ROC and therefore an important observation. The ability to program the samples and to set a sufficient supply current allows to perform basic tests of the readout chain using test pulses. It was found that the pulse height readout is not radiation hard enough for doses beyond ≈ 1 MGy. The reason for this could be identified and the respective change in the design has been included in the layout of the layer 1 ROC. It is important to note that for doses relevant for the layer 2 – 4 ROC of up to 0.5 MGy, no limitations for the pulse height readout are expected. Binary hit information could be read out from all samples even at the highest dose of 4.2 MGy without significant pixel defects.

4.3 Preamplifier noise

In order to efficiently operate the ROC at a low threshold of about 1500 – 2000 electrons it has to be ensured that the noise of the preamplifier stays well below this threshold after irradiation. Test pulses of increasing amplitude are injected to individual pixels and the resulting turn-on of the

efficiency around the threshold is fitted with an error function. Under the assumption of Gaussian distributed noise the width of the error function can be used to estimate the preamplifier noise in units of the test pulse DAC. In order to convert the result into a charge equivalent, an external energy calibration of the ROC has to be applied. This energy calibration uses mono-chromatic X-radiation as reference energies and yields a conversion factor of 46.4 ± 2.5 electrons per test pulse unit. After irradiation the conversion factor changes because of the shift of the band gap reference voltage. Therefore, the shift of the reference voltage is taken into account when measuring the noise after irradiation. Figure 4 shows the preamplifier noise for the SCM samples at different doses. The error bar corresponds to the spread of the noise of all pixels in a given sample. It can be seen that the noise stays at a very low level for the doses relevant for layers 2 and 1 of the detector. The slight decrease of the noise, compared to the result obtained before irradiation, was found to be a consequence of the re-optimization of the shaper feedback resistor after irradiation. Even for the highest doses the noise stays below 200 electrons and thus far below the targeted pixel threshold. The rise of the noise towards high doses is at least partially caused by the higher input capacity caused by under-depletion of the sensors.

4.4 Threshold

Figure 5. Mean and width of the pixel threshold distributions at different doses.

Figure 6. Width of the threshold distribution as a function of dose.

As motivated in Section 1, a low pixel threshold is an important feature of the new ROC. Additionally, the variation of the threshold among the pixels should be small in order to guarantee homogeneous pixel responses for low signals. The threshold is controlled by a global DAC and by four individual trim bits per pixel for fine-tuning, where the scale of the trim bits is set by a second global DAC. A pixel threshold of about 1850 electrons (Figure 5) with a pixel-to-pixel spread below 80 electrons (Figure 6) can be set after irradiation up to 4.2 MGy, showing that all DAC ranges are sufficient and that the threshold bits are functional. Bare ROC samples show narrower threshold distributions because of the lower input capacity without the silicon sensor and the resulting lower preamplifier noise.

4.5 Comparator timing

Figure 7. Comparator timewalk as function of the amplitude of the signal for different doses.

Figure 8. Hit finding efficiency as function of pixel hit rate.

Operating the ROC at a low threshold not only requires low noise and the ability to set a low and homogeneous threshold but also poses stringent demands on the comparator timing. The timing difference for signals with different amplitudes, arising from amplitude dependent rise-times of the signal, are usually referred to as timewalk. Dictated by the LHC bunch spacing, the timewalk is required to stay below 25 ns in order to prevent small signals to be assigned to wrong events. Figure 7 shows the timewalk as function of the signal amplitude, measured with respect to a large signal of about 83 ke. The figure shows that the timing difference stays well below the 25 ns boundary, showing that even very small signals are assigned to the correct bunch crossing when the ROC is operated at a threshold of 1850 electrons for all tested irradiation doses.

4.6 Hit finding efficiency

All measurements described above rely on internal test pulses to assess different properties of the ROC after irradiation. However, it is important to also test the samples under more realistic conditions. This implies to operate the ROC at a low threshold of about 2000 electrons, with high occupancy, and with all pixels sensitive to possible noise sources and external signals. To this end SCM samples irradiated up to a dose corresponding to the expected layer 1 dose of 1.1 MGy have been exposed to X-radiation with hit rates up to 300 MHz/cm² to create readout traffic. Additionally, test pulses have been injected to measure the hit finding efficiency as a function of hit rate. Hereby the efficiency is defined as the ratio between the number of correctly read out test pulses and the number of sent test pulses for each pixel, where correctly read out means that the test pulse could be found in the correct pixel and in the correct bunch crossing. Figure 8 shows that a high hit finding efficiency of 99.5% has been measured for the expected layer 2 hit rate of 120 MHz/cm² and that no degradation of the efficiency could be observed after irradiation for relevant rates.

5. Summary

The CMS pixel detector will be replaced during an extended year-end technical stop of the LHC in winter 2016/17, in order to maintain the physics performance after the design luminosity of the present detector has been exceeded by the LHC. In the upgraded detector a new digital readout chip will be employed to account for the increased occupancy and to ensure sufficient radiation tolerance of the detector. This paper presented a study on the radiation tolerance of the readout chip which will be used in the barrel layers 2 – 4 and in the endcaps of the new detector. It could be shown that the performance of the ROC stays excellent up to its expected lifetime TID of 0.5 MGy, a dose corresponding to 500 fb^{-1} at the distance of the layer 2 ROC from the interaction point. Furthermore, results obtained at higher irradiation levels contributed to finalize the design of layer 1 ROC which was under design at the time when this study was performed, and experiences with irradiated samples helped to define the detector's supply voltages necessary for successful operation after irradiation. Besides investigations on dose levels relevant for the operation of the ROC in the upgraded CMS pixel detector, it could be shown that the current design in 250 nm CMOS technology is radiation tolerant enough to read out binary hit information from test pulses with ROCs irradiated up to 4.2 MGy and that performance parameters such as preamplifier noise, threshold width, and timewalk stay well under control up to the highest doses.

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