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Performance of the modules for layer 1 of the CMS phase 1 pixel detector upgrade

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Abstract

The instantaneous luminosity of the Large Hadron Collider will increase to up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ by 2023. In order to cope with such luminosities, the pixel detector of the CMS experiment has been replaced in January 2017. The upgraded detector features four sensitive layers in the barrel part. A designated readout chip (PROC600V2) is used for layer 1, which is closest to the interaction point and therefore has to handle larger particle fluxes. An irradiation campaign has been performed with PROC600V2 to verify its radiation tolerance up to the maximum expected dose for 2017 of 0.2 MGy. Modules for layer 1 have been built with PROC600V2 for the detector production. The quality of every inserted module was assessed in a number of tests, some of which were performed using X-radiation. The characteristics of the modules used in the detector as well as the main failure modes will be presented.

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Performance of the modules for layer 1 of the CMS phase 1 pixel detector upgrade

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KEYWORDS: Front-end electronics for detector readout, Particle tracking detectors, Radiation-hard detectors, Radiation-hard electronics

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1 Introduction

The CMS detector at the Large Hadron Collider is a multi-purpose high energy physics detector consisting of several sub-detectors which aim to detect particles created in proton-proton collisions [1].

The pixel detector is the subdetector located closest to the beam line and is used to measure the tracks of charged particles by interpolating their interaction points with several layers of detecting material.

In 2008, the phase 0 pixel detector was installed in CMS and has performed excellently until the end of 2016. However, since it was only designed for an instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which will be exceeded by a factor of two by 2023, and due to the fact that it has accumulated significant radiation damage during its eight years of operation, the detector was replaced in January 2017 by a new version, the phase 1 upgrade.

2 The phase 1 upgrade of the CMS pixel detector

In order to maintain or even to surpass the excellent performance of the phase 0 pixel detector at higher instantaneous luminosities, a variety of new developments were introduced for the phase 1 pixel detector.

The phase 1 upgrade of the pixel detector features four layers in the barrel part compared to three layers in the old detector and three instead of two disks in each endcap. With respect to the previous detector, the innermost layer has been moved closer to the beam line and is now located just 3 cm instead of previously 4.4 cm from the beam line. This will lead to a much improved b-tagging efficiency, since b-tagging algorithms rely on an excellent secondary vertex resolution of the pixel detector. Furthermore, a fourth layer has been installed in order to close the gap between the pixel and the strip detector, thus doubling the number of readout channels and therefore

contributing to an improved tracking performance. The material budget in the detector has been reduced by moving part of the readout electronics outside of the detector and by introducing a new bi-phase CO₂ cooling. This new cooling system also allows a lower operation temperature which will be essential since the expected accumulated dose will be much higher for the phase 1 than the phase 0 detector. Furthermore, a new DC-DC powering system has been developed. In order to cope with the larger particle fluxes at higher luminosities, the datastream is now digitized directly on the readout chip (ROC), thus going from a 40 MHz analog readout to a 160 Mbit/s digital readout [2].

3 PROC600V2 for layer 1 of the upgraded pixel detector

The readout chip used for the upgraded pixel detector was designed by the PSI High Energy Physics group. It is based on a 250 nm CMOS technology and consists of an array of 4160 pixels each with a size of $150 \times 100 \mu\text{m}^2$. The pixels are arranged in double columns of 180 pixels, which share 80 buffers for data and 24 buffers for timestamps in the double column periphery where hit information is stored until validation from the CMS level 1 trigger. The properties of the ROC such as its threshold can be tuned with a set of Digital to Analog converters. It is also possible to inject test pulses in the readout chip which follow the same readout chain than hits created by particles. This functionality simplifies the testing of the ROCs' properties [2].

A pixelated silicon sensor is bump bonded to the ROCs, in which particles interacting with the pixel detector create electron-holes pairs. The collected charge is propagated to the ROC, where it is amplified and shaped, via the bump bond. The signal is then compared to an adjustable threshold and is further propagated to the double column periphery if it exceeds that threshold.

Two new readout chips were designed for the detector. While the same chip is used for layers two to four and for the endcaps, a dedicated chip (PROC600V2) equips layer one, because this layer is closest to the beam line, and therefore has to cope with larger particle fluxes. In order to face this challenge, it features a new readout mechanism, reading out clusters of four pixels simultaneously instead of single pixels as is the case for the chip used in the outer layers of the detector. This increases the readout speed by a factor 2.4 at the maximum expected rate of $\sim 600 \text{ MHz/cm}^2$, where on average 1.2 clusters with a size of 1.95 pixels are created per double column. More details about the design of PROC600 can be found in [3].

4 Radiation tolerance of PROC600V2

Irradiation procedure

The phase 1 upgrade of the pixel detector is expected to be operated until the year 2023 when it will be replaced by the phase 2 upgrade. It will be used for over six years, and layer 1 will accumulate a total maximum dose of approximatively 1 MGy during that time. It is therefore very important to verify the radiation tolerance of each of the components of the detector, and of its readout chip in particular. For this purpose an irradiation campaign was performed with ten PROC600V2 samples, which were bump bonded to a silicon sensor, at the 23 MeV proton beam at the Zyklotron AG in Karlsruhe, Germany [4]. All samples were irradiated successively to doses of 0.1 MGy and 0.2 MGy. Further doses of 0.4, 0.6 and 0.8 MGy are planned to study the performance of the

ROC during its entire operation time. A similar study has been performed with PROC600, the first version of the readout chip and with PSIdigV2.1respin, the ROC used for layers 2 to 4, to doses of up to 4.2 MGy, and no significant defects originating from irradiation were observed [3, 5].

All ROCs were tested and kept at -20° after irradiation to prevent annealing effects as well as to operate the chip at a low leakage current also after irradiation. During irradiation, the samples were powered and cooled to about -30°C in order to reproduce the conditions during operation in CMS as close as possible.

Results of irradiation campaign

After all irradiation steps, the functionality of the readout chain in the ROC is verified. This is done by injecting a number of test pulses in each pixel, and by calculating the fraction of test pulses that were read out in the correct pixel in the right bunch crossing. No additional pixel defects were observed after irradiation, as can be seen in Figure 1, which shows the fraction of correctly read out test pulses for a ROC irradiated to 0.2 MGy.

Figure 1. Pixel functionality test showing the efficiency ε of the readout chain after 0.2 MGy.

Figure 2. Threshold of the tested ROCs at each irradiation step.

For operation of the detector, the threshold of all pixels is set to a uniform value and the noise needs to remain low also after irradiation. To measure these quantities, the pixel efficiency is evaluated for different values of the strength of the test pulse around the threshold. The obtained turn-on curve is fitted with an error function, where the point of half maximum corresponds to the threshold and the width to the noise. Figure 2 shows the threshold of the ROCs for all irradiation doses, where the central value corresponds to the mean of the threshold of all pixels and the error bar to their standard deviation. It can be seen that the same physical threshold of 2000 e^- can be set at all irradiation doses and that the width of the threshold distribution amongst the pixels also remains constant. It is important to be able to set such a low threshold since the charge collection efficiency decreases with irradiation. This proves that the range of the DACs available to tune the threshold and of the trim bits, which are used to adjust the threshold of every pixel individually, is sufficient and that their functionality is not affected at these irradiation doses.

Figure 3. Noise of the ROCs as a function of irradiation dose measured with only one pixel enabled at the time.

Figure 4. Noise of the ROCs as a function of irradiation dose measured with all pixels enabled and while exposing the ROC to X-radiation at a rate of $\sim 300 \text{ MHz/cm}^2$.

The preamplifier noise of the ROCs is measured for all pixels successively in two different conditions. Once, it is measured with only one pixel enabled at the time, and once with all pixels operating simultaneously while exposing the ROC to the maximum particle hit rate expected within CMS to reproduce the operation conditions as close as possible. The noise as a function of irradiation dose can be found respectively in Figures 3 and 4, where the central value corresponds to the mean noise of all ROCs at the given irradiation dose and the error to their standard deviation. While the noise without X-radiation is very low at around 115 e^- and is stable for all tested irradiation doses, the noise increases to approximately 400 e^- when exposing the ROCs to X-radiation. This can be explained by higher occupancies and data fluxes within the readout chain of the pixels. It can also be noticed that the noise appears to increase slightly with irradiation at a rate of $20 \text{ e}^-/0.1 \text{ MGy}$. This feature has not been understood yet and needs further investigation at increasing irradiation doses.

Collisions in CMS occur every 25 ns, therefore it is essential that the timewalk, which gives the difference between the time at which a pulse with large and a pulse with small amplitude cross the threshold, is less than 25 ns. This has been verified by measuring the timewalk between a pulse of $\sim 83 \text{ ke}^-$ and a test pulse of varying strength approaching the threshold, as can be seen in Figure 5. As expected, the timewalk increased with test pulses strengths approaching the threshold, but it always remains below the required 25 ns.

The efficiency of all ROCs has been measured at different X-ray hit rates. It is measured in the same way as used when testing the pixel functionality, however, the ROC is simultaneously exposed to X-radiation in this case. The efficiency for all pixels of one ROC at a photon hit rate of $\sim 500 \text{ MHz/cm}^2$ can be seen in Figure 6 which shows, as expected, that the efficiency decreases with high hit rates. The efficiency of the border pixels is lower since their size is twice larger than that of the other pixels. The efficiency as a function of particle hit rate is shown in Figure 7. Due to

Figure 5. Timewalk as a function of test pulse strength for all irradiation doses.

Figure 6. Efficiency of all pixels of a ROC before irradiation at a photon hit rate of ~ 500 MHz/cm².

Figure 7. Efficiency of the ROCs as a function of the pixel hit rate at different irradiation doses. The maximum expected particle hit rate in CMS corresponds to a photon hit rate of ~ 300 MHz/cm².

Figure 8. Number of hits acquired per pixel of a ROC. A region with many pixels detecting no hits is clearly identifiable in the bottom left corner, indicating defective bump bonds.

a difference in the size of the clusters created by incoming photons and charged particles, the maximum expected hit rate in CMS of 600 MHz/cm² corresponds to a photon hit rate of 300 MHz/cm². The efficiency at all irradiation doses is above 99% at this rate, and the massive decrease in efficiency caused amongst others by the finite number of data and timestamp buffers only appears at a photon hit rate of ~ 600 MHz/cm², thus ensuring a good efficiency even if the instantaneous luminosity slightly exceeds the expected one.

5 Performance characterization of the layer 1 modules

Layer 1 modules for the phase 1 upgrade consist of a silicon sensor which is bump-bonded to sixteen PROC600V2. A high density interconnect is glued on the ROCs in order to provide power as well as to synchronize the readout. A carbon fibre clip is used to fix the module to the support structure of the detector.

The quality of all built modules was assessed before installation. To this end, the programmability of the module and of all 16 ROCs were tested, the supply voltages and the threshold were calibrated, the noise was measured and the quality of the sensor was evaluated. Some additional tests were performed while exposing the module to X-radiation to test its interaction with real particles and to validate the efficiency of the module in a high hit rate environment. With this, several defects leading to a decrease in efficiency such as faulty bump bonds or broken buffers could be identified, and contributed in selecting only modules with good quality for the detector.

By exposing the modules to X-radiation for a sufficient amount of time, defective channels can easily be identified as pixels which do not record any incoming particles. For example this could originate from defective bump bonds indicating a broken connection between the silicon sensor and the readout chip. Clearly, hits occurring in such pixels will not be detected since the charge can not be properly read out by the ROC. Therefore, all pixels which are able to process test pulses but which did not detect any hits can be identified as pixels with defective bump bonds. An example of a severely affected module is shown in Figure 8.

Another explanation for dead channels can be a defective double-column environment which features buffers where data and timestamp information is stored until trigger validation. During testing, the modules are exposed to rates high enough such that all buffers are used simultaneously. It was observed that for a significant fraction of all tested modules (13%), a whole double column became irresponsive in such conditions, therefore leading to a reduced efficiency in that double column at high X-ray rates. This is illustrated in Figure 9.

These issues are obviously reflected on the efficiency of the ROCs installed on the modules. The efficiency is measured using the same procedure than during the radiation hardness study of PROC600V2 and the result is shown in Figure 10. Installable modules are represented in green, and each marker corresponds to the efficiency of one ROC at a given X-ray hit rate. It can be observed that the efficiency for all installed modules is well above 99% at the maximum hit rate expected in CMS of 300 MHz/cm^2 . Modules with various kinds of defects, such as defective bump bonds or buffers leading to lower efficiencies are clearly identifiable.

A total of 136 modules were built for layer 1 of the upgraded detector. The quality of 97 modules was satisfactory and 96 modules were installed in the detector, leading to a yield of 71%. The main failure modes were defective double columns and sensor defects leading to a high leakage current. In two cases, modules were also rejected because of a very large number of defective bump bonds.

6 Conclusion

The quality of the modules installed in layer 1 of the Phase 1 upgrade of the CMS pixel detector has been assessed in multiple ways. In particular, the radiation tolerance of the ROC used for these

Figure 9. Number of hits acquired per pixel of a ROC. Columns 40 and 41 did not acquire any hits because of defective buffers in the double column periphery.

Figure 10. Efficiency of the ROCs on all tested modules as a function of the pixel hit rate. The maximum expected particle hit rate in CMS corresponds to a photon hit rate of $\sim 300 \text{ MHz/cm}^2$.

modules (PROC600V2) has been studied in an irradiation campaign. It showed that no radiation induced damages are expected to appear which could lead to a reduced performance of the detector. Furthermore, the quality of each installed module has been verified. For example, tests performed under X-radiation enabled to identify modules with defects leading to a reduced efficiency, such as problematic buffers in the double column periphery. Only modules showing no irregularities have been used for the detector, thus ensuring its good quality.

Acknowledgments

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