Journal of Instrumentation

High rate capability and radiation tolerance of the PROC600 readout chip for the CMS pixel detector

*J*inst

Published by IOP Publishing for Sissa Medialab

Received: *October 26, 2016*
Accepted: *December 20, 2016*
Published: *January 25, 2017*

Pixel 2016 International Workshop
September 5 – September 9, 2016
Sestri Levante, Genova, Italy

High rate capability and radiation tolerance of the PROC600 readout chip for the CMS pixel detector

A. Starodumov,[1] P. Berger and M. Meinhard on behalf of the CMS collaboration

IPP, ETHZ,
Otto-Stern-Weg 5, Zurich, 8093 Switzerland

E-mail: andrey.starodumov@cern.ch

Abstract: The first layer of the CMS Phase 1 pixel detector will be located at a distance of 3 cm from the interaction point. Pixel hit rates up to 600 MHz/cm^2 are expected at the instantaneous luminosity of $2{\times}10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ foreseen by LHC in the coming years. The CMS Phase 1 pixel detector will be in operation until 2024/25 and the total fluence received by the first layer in its lifetime will reach $2\text{–}3{\times}10^{15}\,\mathrm{n_{eq}/cm^2}$ that corresponds to 0.8–1.2 MGy. A new readout chip, called PROC600, to be used for layer 1 modules has been designed at PSI. To validate robust and efficient operation of PROC600, it has been irradiated to doses ranging from 0.6 MGy up to 4.8 MGy. The chip performance before and after irradiation including the pixel hit efficiency will be presented.

Keywords: Front-end electronics for detector readout; Hybrid detectors; Radiation-hard detectors; Radiation-hard electronics

2017 JINST 12 C01078

[1]Corresponding author.

doi:10.1088/1748-0221/12/01/C01078

Contents

1 Introduction

The Large Hadron Collider (LHC) constantly increases its peak luminosity and aims to reach $2{\times}10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the coming years. The present CMS pixel detector [1] has been designed for efficient operation at $1{\times}10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Dynamic data losses of the pixel readout chip (ROC) significantly grow at higher collision rates. To maintain equal or better performance at the higher luminosity, the CMS Phase 1 upgrade pixel detector [2] is being built. The installation of this detector is foreseen during an extended year-end technical stop in February 2017. A new readout chip — PROC600 — has been designed in the past few years to cope with the flux expected at the innermost layer of the pixel detector.

The paper is organised as follows. In section 2 the main features of the upgraded pixel detector will be briefly summarised. The main design properties of PROC600 will be described in section 3. Results of high rate hit efficiency measurements and performance of the readout chip before and after irradiation are presented in sections 4 and 5.

2 CMS Phase 1 upgrade pixel detector

The detailed description of the upgraded CMS pixel detector can be found elsewhere [3]. Here the main features of the pixel detector and the expected operating conditions are briefly presented.

The upgraded pixel detector consists of 4 barrel cylindrical layers and 6 forward disks, instead of 3 layers and 4 disks, respectively, of the present detector. The radius of the innermost barrel layer is reduced to 3 cm instead of the present radius of 4.2 cm. The material budget remains the same or even decreases in forward/backward directions thanks to a new two-phase CO_2 cooling system, a light-weight mechanical support and a relocation of electronics boards out of the tracker acceptance. Instead of direct powering a new power system based on a DC-DC conversion scheme will be used. To sustain significantly higher data readout traffic, a faster front-end DAQ system based on μTCA instead of VME technology is developed. Finally, two new readout chips are designed: PSI46dig [4] for the barrel layers 2 to 4 and the forward disks and PROC600 for layer 1 of the barrel detector.

The maximum expected pixel hit rate at layer 1 ranges from 420 MHz/cm^2 (based on an occupancy radial dependence as measured by the present pixel detector) up to 580 MHz/cm^2 (based on PYTHIA [5] MC simulations). These rates are significantly higher than 120 MHz/cm^2 expected at layer 2 and require a new readout logic to maintain acceptable hit efficiency. Such a chip, called PROC600 (**PSI** **ROC** for **600** MHz/cm^2), has been designed for layer 1.

The CMS Phase 1 pixel detector will be in operation for the next 5–6 years. The total particle fluence received by the first layer during this time is expected to be 2–3$\times 10^{15}$ n_{eq}/cm^2. This means that layer 1 should withstand radiation doses up to 1.2 MGy corresponding to an integrated luminosity of 300 fb^{-1} to be collected by the pixel detector during its lifetime.

3 PROC600 design properties

PROC600 is based on the same 250 nm CMOS technology as the PSI46dig chip. Both ROCs have the same analog pixel front end and most of the chip periphery while the digital part of the double column and the pulse height readout are entirely new. The ROC size is 7.86$\times$10.5 mm^2 and it consists of three parts. The first one is a 4160 pixel array arranged in 52 columns and 80 rows with a pixel size of 150$\times$100 μm^2. The second part is composed of an interface of 26 double columns each containing a data buffer with 56 buffer cells (each cell stores a 2$\times$2 pixel cluster address and the four analog pulse heights) and one 40 cell deep time stamp buffer. The third part is a control interface block where readout logic, DACs, I^{2}C interface, ROC readout buffer, 8 bit ADC etc. are located.

Several new features are implemented in the new ROC. The main ones are 1) a checkout mechanism that allows the column drain to run continuously and does not require a buffer reset; 2) a different communication logic design between the pixel unit cell and the periphery that allows for 7 pending column drains instead of 3 and 3) a new 40 MHz Dynamic Cluster Column Drain (DCCD) mechanism. In the following only the DCCD mechanism will be described in details.

At a high particle flux a few pixels in one double column may be hit in the same bunch crossing. In PSI46dig such hits are drained one after another and $2 \times \mathbf{n} + 3$ clocks are required to readout **n** pixels. If more hits at a time were read out, the dead time and the consequent pixel inefficiency would be reduced. Under CMS conditions a charged particle creates on average a cluster of two adjacent pixels in one double column. The DCCD mechanism reads out a 2$\times$2 pixel cluster even if not fully occupied and $\mathbf{m} + 2$ clocks are needed for readout **m** clusters. Since the mean number of clusters at 600 MHz/cm^2 is about 1.2 per a double column and a bunch-crossing, such readout scheme provides a gain of 2.4 in speed.

All the improvements implemented in PROC600 allow to contain its inefficiency within 2% at the pixel hit rate of 600 MHz/cm^2.

4 High rate efficiency of PROC600

The high rate performance of PROC600 has been tested with X-rays in a laboratory test stand and with protons in test beams. For these tests a chip has been bump-bonded to a silicon sensor and glued to a PCB to connect it to the readout electronics. X-rays produce mostly one pixel hit clusters.

2017 JINST 12 C01078

Protons deposit energy along their flight path in the silicon bulk and by changing their incident angle, the average cluster size can be tuned to any desired value, e.g. two pixel hits per cluster.

The pixel efficiency is measured with the help of an internal calibration mechanism of the ROC that permits to send a test signal to a chosen pixel followed by a trigger that initiates the readout of this pixel. External particles, X-rays or protons, are used to create data traffic in the ROC and sometimes a test hit is lost due to high occupancy of the double column to which the pixel belongs. To measure the hit rate and the efficiency one has to count the number of hits from external particles and separately the number of hits from internal test signals. The pixel hit efficiency ε is the ratio of the number of readout hits from test signals and the number of sent test signals: $\varepsilon = \mathrm{n}_{\text{cal, readout}}/\mathrm{n}_{\text{cal, sent}}$.

The hit rate from the external source can be measured consistently counting the number of readouts. It is assumed that such hits have the same efficiency ε that is measured with help of the internal calibration mechanism. Hence the hit rate per cm^2 is calculated by the following formula:

$$R = \frac{n_{\text{hits}}}{n_{\text{trig}} \cdot t_{\text{BC}} \cdot A_{\text{active}} \cdot \varepsilon}, \tag{4.1}$$

where n_{hits} is the total number of readout hits, n_{trig} is the number of sent triggers during the data taking, $t_{\text{BC}} = 25$ ns is the bunch-crossing length, A_{active} is the active area of the silicon sensor readout by the chip and ε is the efficiency calculated above.

A direct X-ray beam is generated by an X-ray diffraction glass tube. The anode current could be set maximum to 50 mA and the high voltage to 60 kV but keeping the power below 1.8 kW. With such parameters an X-ray hit rate up to 1 GHz/cm^2 could be achieved.

A focused 200 MeV proton beam with a bunch frequency of about 70 MHz is used to measure the PROC600 hit efficiency at the Proton Irradiation Facility [6] (PIF) at Paul Scherrer Institute (Villigen, Switzerland). The sample is mounted on a frame that can be rotated allowing tilting it with respect to the beam (figure 1, left) and hence varying the cluster size. During data taking the sample is tilted by 20° about the z-axis and then about both the y- and z-axes by 20° as well (figure 1, right) to emulate different pixel hit topologies in a 2×2 readout frame and confirm that efficiency does not depend on them. The average cluster size is close to two pixels in both cases.

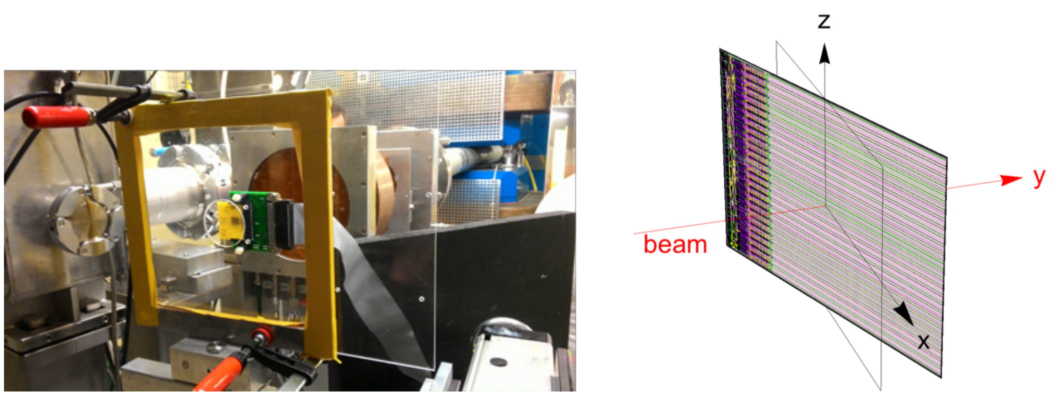

Figure 1. Left: picture of the setup at PIF with the sample mounted in a frame that can be rotated. Right: sketch illustrating an orientation of the chip and the direction of the proton beam.

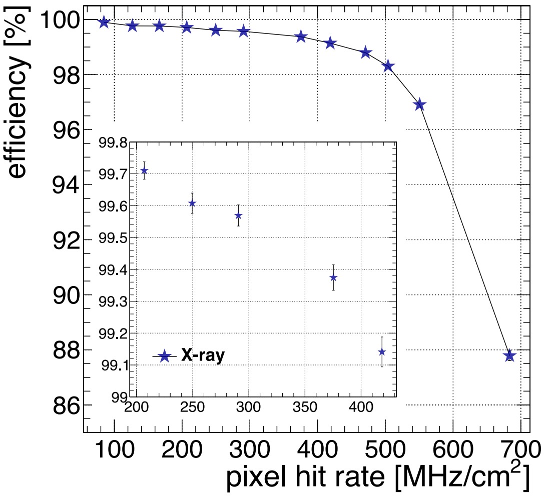

Figure 2. Efficiency measured with X-rays. At the X-ray rate of 300 MHz/cm^2 the efficiency is 99.6%.

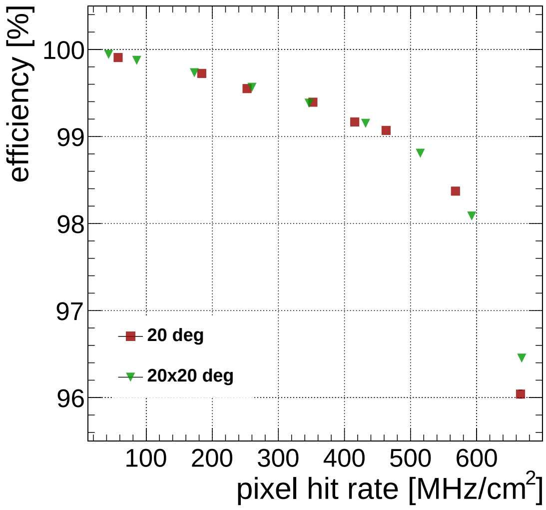

Figure 3. Efficiency measured with protons. At the pixel hit rate of 600 MHz/cm^2 the efficiency is about 98%.

Each pixel cluster is attached to one time stamp but could occupy more than one data buffer cell. Since the time stamp buffer is shorter than the data buffer and X-rays produce single-hit pixel clusters, the efficiency is mostly limited by the number of time stamp buffer cells. For realistic CMS run conditions, one time stamp buffer cell could correspond to up to four data buffer cells and the average number of pixel hits is two. Hence, mainly the efficiency of the time stamp buffer as expected in CMS at 600 MHz/cm^2 can be studied with an X-ray rate of 300 MHz/cm^2. At 300 MHz/cm^2 the efficiency is 99.6% as it is seen in figure 2.

The overall efficiency of PROC600 has been tested with the proton beam at PIF. Due to more hits created per one proton than per one photon other sources of chip inefficiency like readout buffer overflow or larger pixel dead time could be tested. Figure 3 shows the efficiency versus the pixel hit rate. In both configurations (tilt angle of 20° about z-axis and of $20° \times 20°$ about y- and z-axes) the hit efficiency is about 98.0%.

5 Radiation hardness of PROC600

In order to emulate the radiation damage expected in the PROC600 during its operating time the ROC has been irradiated with a 23 MeV proton beam at the Zyklotron AG in Karlsruhe (Germany) [7]. This study aims to determine how the functionality parameters of the chip change after irradiation and whether the range of the tuneable DACs is sufficient for high performance operation. PROC600 has been exposed to the total ionisation doses (TID) of 0.6 and 1.2 MGy to emulate conditions expected in the CMS experiment as well as to 2.4 and 4.8 MGy to test the limits of the chip. Table 1 summarises the target and actually received doses, proton and 1 MeV neutron equivalent fluences. All samples after irradiation were kept one hour at a room temperature, before the handling was allowed, and then — at temperatures below zero degree Celsius. 70% of samples were powered during irradiation and 30% — not. No differences between two cases were observed.

2017 JINST 12 C01078

Table 1. Summary of the target and measured radiation doses, the corresponding proton and 1 MeV neutron equivalent fluences, and the number of samples per dose.

Target dose (MGy)	Measured dose (MGy)	Proton fluence (p/cm^2)	Neutron fluence (n/cm^2)	# of samples
0.60	0.66	0.2×10^{15}	0.4×10^{15}	4
1.20	1.37	0.4×10^{15}	0.8×10^{15}	5
2.40	2.65	0.8×10^{15}	1.6×10^{15}	3
4.80	4.95	1.6×10^{15}	3.2×10^{15}	3

One of the main conditions to operate the ROC is to properly power its analog and digital circuits. It was verified that dynamic ranges of DACs responsible for power setting are sufficient to provide necessary current.

Due to radiation damage of the silicon sensor the charge collected by a pixel decreases, hence a possibility to set a low threshold after irradiation increases the longevity of a ROC. It was shown that the trimmed threshold of the PROC600 can be kept at the same value of 2000 e$^-$ as before irradiation with a noise below 120 e$^-$ up to the highest dose.

The timewalk is another important feature that characterises the chip performance. Low pulses have a longer rise time than high pulses. If the difference between the rise time of a large signal and a low one (timewalk) is larger than the time between neighbour bunch-crossings of 25 ns the low signal will not be detected. Figure 4 shows the timewalk as a function of the test pulse charge for different irradiation doses, proving that, despite a slight increase after irradiation, the timewalk of the PROC600 remains below 15 ns.

The pixel hit efficiency after irradiation has been measured using the high rate X-ray setup described in section 4. Figure 5 shows that there is no significant decrease in efficiency at 300 MHz/cm^2. The efficiency of the PROC600 is 99.4% at the highest irradiation doses of 1.2 MGy.

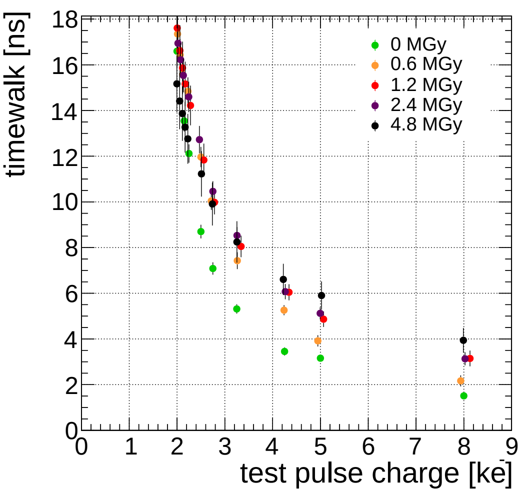

Figure 4. Timewalk of PROC600 before and after irradiation.

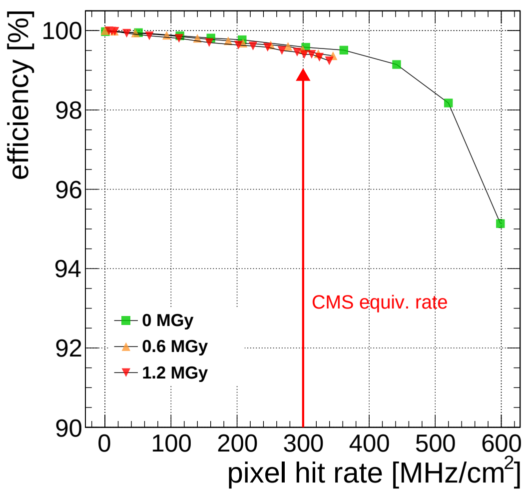

Figure 5. Efficiency of PROC600 before and after irradiation.

6 Conclusion

The new digital readout chip PROC600 will be operating at 3 cm from the LHC interaction region. Because of the high particle flux and high ionisation doses, its performance before and after irradiation has been investigated.

PROC600 has demonstrated excellent performance with an efficiency of 99.6% measured with an X-ray rate of 300 MHz/cm^2 and 98% measured in a proton test beam at 600 MHz/cm^2, fulfilling its design specifications.

The ROC remains fully operational after irradiation to a target dose of 1.2 MGy and maintains its performance. The PROC600 threshold could be trimmed to the same low value of 2000 e$^-$ as before irradiation with a noise as low as 120 e$^-$. The timewalk does not increase and stays well below a bunch crossing length of 25 ns. The hit efficiency of the chip irradiated to 1.2 MGy has been measured with an X-ray setup without any noticeable decrease up to 300 MHz/cm^2. Even at doses of 2.4 and 4.8 MGy PROC600 maintains most of the above mentioned performance characteristics.

Acknowledgments

In this paper the work of many people from the CMS Pixel Phase 1 Upgrade community is summarised. The authors would like to thank all of them. Special thanks to R. Horisberger (PSI), H.-Ch. Kaestli (PSI), B. Meier (PSI), T. Rohe (PSI), S. Streuli (PSI), M. Donega (ETHZ) and M. Reichmann (ETHZ).

The irradiation campaign has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

References

[1] W. Erdmann, *The CMS pixel detector*, *Int. J. Mod. Phys.* **A 25** (2010) 1315.

[2] CMS collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade*, CERN-LHCC-2012-016 (2016).

[3] V.R. Tavolaro, *The Phase1 CMS Pixel detector upgrade*, 2016 *JINST* **11** C12010.

[4] D. Hits and A. Starodumov, *The CMS Pixel Readout Chip for the Phase 1 Upgrade*, 2015 *JINST* **10** C05029 [CMS-CR-2014-450].

[5] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175].

[6] Proton Irradiation Facility at Laboratory For Particle Physics, PSI, Villigen, Switzerland http://pif.web.psi.ch/.

[7] Zyklotron AG, Karlsruhe, Germany http://www.zyklotron-ag.de/en/.

2017 JINST 12 C01078