The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

11 September 2017 (v2, 18 September 2017)

The construction of the phase 1 upgrade of the CMS pixel detector

Hannsjoerg Weber for the CMS Collaboration

Abstract

The innermost layers of the original CMS tracker were built out of pixel detectors arranged in three barrel layers and two forward disks in each endcap. The original CMS detector was designed for the nominal instantaneous LHC luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Under the conditions expected in the coming years, which will see an increase of a factor two of the instantaneous luminosity, the CMS pixel detector would have seen a dynamic inefficiency caused by data losses due to buffer overflows. For this reason the CMS collaboration has installed during the recent extended end of year shutdown a replacement pixel detector.

The phase-1 upgrade of the CMS pixel detector will operate at high efficiency at an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with increased detector acceptance and additional redundancy for the tracking, while at the same time reducing the material budget. These goals are achieved using a new read-out chip and modified powering and read-out schemes, one additional tracking layer both in the barrel and in the disks, and new detector supports including a CO_2 based evaporative cooling system, that contribute to the reduction of the material in the tracking volume.

This contribution will review the design and technological choices of the phase-1 detector.

Presented at *PSD11 Position Sensitive Detectors 11*

PREPARED FOR SUBMISSION TO JINST

11TH INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS

3-8 SEPTEMBER 2017

OPEN UNIVERSITY, MILTON KEYNES, UK

The construction of the phase-1 upgrade of the CMS pixel detector

Hanns Jörg Weber^{a,1}

^a*Fermilab,
Batavia IL, USA*

E-mail: haweber@cern.ch

ABSTRACT: The innermost layers of the original CMS tracker were built out of pixel detectors arranged in three barrel layers and two forward disks in each endcap. The original CMS detector was designed for the nominal instantaneous LHC luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Under the conditions expected in the coming years, which will see an increase of a factor two of the instantaneous luminosity, the CMS pixel detector would have seen a dynamic inefficiency caused by data losses due to buffer overflows. For this reason the CMS collaboration has installed during the recent extended end of year shutdown a replacement pixel detector.

The phase-1 upgrade of the CMS pixel detector will operate at high efficiency at an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with increased detector acceptance and additional redundancy for the tracking, while at the same time reducing the material budget. These goals are achieved using a new read-out chip and modified powering and read-out schemes, one additional tracking layer both in the barrel and in the disks, and new detector supports including a CO₂ based evaporative cooling system, that contribute to the reduction of the material in the tracking volume.

This contribution will review the design and technological choices of the phase-1 detector.

KEYWORDS: Particle tracking detectors

¹for the CMS Tracker Group

Contents

1	Introduction	1
2	The new read-out chips and pixel module	2
3	Mechanical support and cooling	4
4	Service electronics	4
5	Status of the detector	5
6	Summary	7

1 Introduction

The CMS experiment [1] is a general purpose detector at the CERN LHC in Geneva, Switzerland. In order to reconstruct the different types of particles originating from the proton-proton (pp) collisions, the CMS experiment utilizes several subdetectors, such as an inner tracker, two calorimeters, and an outer muon tracker. The inner tracking detector [2, 3] of the CMS experiment is made out of the pixel tracker and a strip detector. Prior to the upgrade, the pixel tracker was arranged in three barrel layers (BPIX) and two forward disks in each endcap (FPIX). It had been designed for the nominal instantaneous LHC luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

It was estimated several years ago that the LHC will exceed its design luminosity, and as a consequence the performance of the pixel detector will degrade because of dynamic inefficiency caused by data losses due to buffer overflows in the front-end read-out chips.

In fact, during the 2016 pp collision runs of the LHC, a significant decrease of pixel hit efficiency in the first layer of the BPIX was observed, as shown in Figure 1.

For this reason the CMS collaboration built a replacement pixel detector [5], which was installed during the extended end-of-year shutdown during winter 2016/2017.

The so-called phase-1 upgrade of the CMS pixel detector was designed to operate efficiently up to instantaneous luminosities of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In order to achieve this, new read-out chips (ROCs) have been designed with larger buffer sizes and higher read-out bandwidth. Another major design change is a new layout of tracking layers: the innermost layer is brought closer to the beam line with a radial distance of 2.9 cm instead of 4.4 cm. Also, an additional tracking layer is introduced for both the barrel and forward regions. This will allow for better vertexing and tracking capabilities, but also adds redundancy.

Even though a new tracking layer has been added to the detector, the passive material was significantly reduced due to a more compact mechanical support together with a new CO₂ cooling system, as well as moving services outside of the tracking volume.

A pictorial comparison between the layout of the former and new pixel detectors is shown in Fig. 2. In the following, the upgrade is discussed in detail.

Figure 1. Hit efficiency vs. instantaneous luminosity during 2016 pp collisions for pixel barrel layers and forward disks. The innermost layer is most affected by dynamic inefficiencies. Taken from [4].

2 The new read-out chips and pixel module

The composition of a pixel module hasn't changed with respect to the former pixel detector: an array of ROCs (2×8 for the upgrade) is bump-bonded to an n^+ -in- n planar silicon sensor via lead bumps. On top, a thin printed circuit, the high density interconnect (HDI), is glued onto the sensor and wire-bonded to the ROCs. A token bit manager (TBM) is placed on the HDI and organizes the data stream of the ROCs. Each module is comprised out 66560 pixels, each with a size of $100 \times 150 \mu\text{m}^2$. The pixel detector has a uniform module layout, which is a substantial simplification with respect to the former detector, that had seven different layouts for modules.

The most important change of the pixel module's design is the new ROC. An 8-bit ADC and a

Figure 2. Comparison of the layout between the upgraded (top) and former (bottom) CMS pixel detector. Taken from [5].

PLL have been added, allowing for a digitized read-out. Thus, the read-out speed has been increased from 40 MHz of the old ROC to 160 Mbits/s. The number of data and timestamp buffer cells is enlarged by at least a factor of 2 to total 80 and 24 buffer cells, respectively. With these two changes, the new pixel detector will overcome the inefficiencies mentioned in Sec. 1. The ROC is designed to be radiation hard, allowing to operate the pixel detector until 2023, after which the detector will be upgraded again [6] to operate in the conditions of the high luminosity-LHC. Further improvements to the chip-internal cross-talk, the comparator and transistors reduce the noise of the chip und thus allow to operate the chip at a low threshold of about 1800 electrons.

The pixel modules in the innermost BPIX layer have to operate at high expected hit rates of up to 600 MHz/cm². Therefore, a special version of the ROC [7] has been designed to handle these hit rates. The chip performs a dynamic cluster column drain where the hit data are transferred in clusters of 2×2 pixels to the buffer instead of the data of single pixels. Another difference for the pixel modules in the first BPIX layer is that two TBMs are placed on the HDI to organize the high-volume data stream of those ROCs.

In total, 1856 pixel modules were installed in the detector resulting in almost twice as many read-out channels as in the former detector (124 million pixels compared to 65 million pixels). They had to pass a rigorous testing procedure: The quality of the connections between different layers, i.e. the bump-bonds between ROCs and sensor and wire-bonds between ROCs and HDI, were tested after thermally stressing them. The high-rate performance of the ROC was measured using X-ray exposure. Further series of tests evaluated the quality of the pixels such as their noise properties or leakage current as a function of the applied bias voltage. The sum of these test results were used to discard modules of poor quality. Two examples of test results are given in Fig. 3.

Figure 3. Left: Read-out efficiency for the ROC for the innermost BPIX layer as a function of the hit rate. The chip is > 99% efficient for hit rates expected at the LHC which is indicated by the red dotted line. Right: Measurement of the pixel turn-on threshold for modules in the FPIX, in ADC units of test voltage setting ($V_{cal} \text{ unit} \hat{=} 50 e^-$). The turn-on is measured after trimming the detector to a threshold of 35 V_{cal} units. Grade A and B modules are of detector-quality, with A being the best quality. Grade C modules are discarded because of deficiencies, such as containing a significant fraction of pixels that are not trimable.

3 Mechanical support and cooling

In Fig. 4, the mechanical structure of the pixel detector is shown. It supports the pixel modules and service electronics, while being of low mass to reduce particle interaction with passive material.

Figure 4. Exploded view of the upgraded pixel detector. The figure shows the positions of the different partitions, FPIX and BPIX, and their respective service cylinders. Taken from [5].

The support structure is made out of a carbon fiber and Airex foam compound for BPIX, and carbon fiber and thermal pyrolytic graphite for FPIX. The pixel modules are held by support strips in the central part, and blades organized on half-disks for the forward part. These support strips and blades are highly thermally conductive, guiding the heat produced in the pixel modules to tubes containing the coolant.

The cooling system is based on bi-phase CO_2 as coolant instead of mono-phase liquid C_6F_{14} that had been used in the former detector. The heat of the detector is absorbed as latent heat of the CO_2 . The cooling system has a nominal operation temperature of -20°C , which requires the CO_2 to be pressurized at about 20 bar. The tubes guiding the CO_2 are made out of stainless steel with an inner diameter of 1.6 mm and a wall thickness between 50 and $100\ \mu\text{m}$. They are embedded in the support structure.

Another significant difference in the mechanical design of the phase-1 and the former detector is that the service electronics for both the BPIX and FPIX pixel modules has been moved further away from the interaction point, thus greatly reducing the passive material within the tracking volume, as shown in Fig. 5.

4 Service electronics

Additional service electronics within the pixel detector is needed to be able to operate the detector.

The first class of electronics is DC-DC converter boards [8]. As the number of read-out channels is almost doubled with respect to the former detector, the power loss in the current detector would have been increased by a factor of about four. The power supplies would not have been able

Figure 5. The amount of material in the pixel detector shown in units of radiation lengths for the former pixel detector (green histogram), and the phase-1 upgrade detector (black points). The shaded region at high $|\eta|$ is outside the region for track reconstruction. Taken from [5].

to handle this amount of loss. Therefore, they are operated at a higher voltage (10 V) and lower current which reduces the power loss significantly. The on-detector DC-DC converters transform the high voltage currents to currents at low voltages (2.4 and 3.0 V for the analog and digital circuits of the pixel modules, respectively). The DC-DC converter boards are cooled with the same cooling circuits as the pixel modules.

The other class of service electronics located within the support structure of the detector aids the control and read-out of the pixel modules. Optical signals for clock and trigger pulses as well as configuration data are sent to the detector. They get converted into electric signals by digital opto-hybrids that are connected to printed circuit boards. Auxiliary chips synchronize the sent signals, translate them from the opto-hybrid's LVDS to the TBM's LCDS standard, and correctly distribute them to each individual module. Also, the jitter in these signals is filtered using a quartz crystal based PLL. The new pixel opto-hybrids [9] host linear laser drivers, level-translator chips, and transmitter optical subassemblies that convert the electric pixel hit data to light, which is sent out of the detector in optical fibers. For the two innermost BPIX layers, the pixel data are transmitted in four or two fibers per pixel module, respectively, while for all other layers, one read-out fiber per module is sufficient to transmit the data.

The data acquisition of the backend electronics for the upgraded detector is based on the μ TCA standard with high-speed links of up to 10 Gbits/s. One class of boards, so-called front-end controllers, distribute the clock, trigger, and configuration signals, and the other class of boards, so-called front-end drivers, process the pixel hit data streams.

5 Status of the detector

The upgrade of the pixel detector was installed during the extended year-end technical stop 2016/2017. All necessary calibrations were performed, and the detector was commissioned using both cosmic data and the first pp collision data of 2017. During the commissioning phase, the

read-out chain had been exercised, and the detector was aligned both in time and space. More details can be found in [10].

Figure 6. The cluster occupancy for the pixel detector during the pp collision data run 297099. In the top row from left to right: the complete FPIX, BPIX layer 1 and layer 2; in the bottom row from left to right: BPIX layer 3 and layer 4. The cluster of non-functional modules in FPIX disk -1 has been recovered during later running. Taken from [11].

A snapshot of the cluster occupancy of the pixel detector is given in Fig. 6: In this figure, each module, a group of 16 ROCs, is indicated by a rectangle with a solid black boundary and the nominal ROC0 (the first ROC of the module receiving the read-out token of the TBM) is also indicated by a solid black border. For the FPIX (top left plot), the disks are displayed according to their z position of the CMS coordinate system [1] along the horizontal axis with the inner disk being at smaller absolute values and outer disk at larger values. The half-disks with negative blade number are on the outer side of the experiment (i.e. with negative x position in the CMS coordinate system). For BPIX (other four plots), the layout is similar, the horizontal axis displays the z position of a module within a ladder, while the ladder position follows the same convention as the blade position for the FPIX. As the indices 0 are not used, each plot contains a white cross.

The snapshot of the cluster occupancy shows overall good quality, but three groups of pixel modules are non-functional: The empty clusters for pixel modules on disk +2 of FPIX and in the fourth layer of BPIX are non-functional due to issues with the corresponding read-out service electronics, while the cluster of pixels in the second and third layer of BPIX is due to an issue in a power group. Thus, the fraction of active pixels of 95.5% is lower than the $> 98\%$ of the former pixel detector. However, due to the increase in redundancy by having one additional layer, the impact on physics is expected to be negligible.

Figure 7 shows the pixel hit efficiency for the upgraded pixel detector as a function of the instantaneous luminosity using 2017 pp collision data. It can be appreciated in comparison with Fig. 1 that the inefficiency observed for the innermost barrel layer of the former detector has been significantly decreased.

Figure 7. Hit efficiency for the upgraded phase-1 pixel detector vs. instantaneous luminosity during 2017 pp collisions for pixel barrel layers and forward disks. Taken from [12].

6 Summary

The phase-1 CMS pixel upgrade has been installed and commissioned in the beginning of 2017. The detector is successfully taking proton-proton collision data with a fraction of $> 95\%$ of pixels being active. Early studies have shown that the inefficiencies that were observed with the former detector are now largely reduced. The phase-1 pixel detector is expected to record collision data with high quality until 2023, after which it will be upgraded for the high luminosity-LHC.

References

- [1] CMS collaboration, S. Chatrchyan et al., *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.
- [2] CMS collaboration, V. Karimäki, M. Mannelli, P. Siegrist, H. Breuker, A. Caner, R. Castaldi et al., *CMS: Tracker. Technical design report*, CERN-LHCC-98-06, CMS-TDR-5 (1998) 1.
- [3] CMS collaboration, *The CMS tracker: addendum to the Technical Design Report*, CERN-LHCC-2000-016, CMS-TDR-5-add-1 (2000) 1.
- [4] CMS Tracker Group, “<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2016>.”
- [5] CMS collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade*, CERN-LHCC-2012-016, CMS-TDR-011 (2012) 1.

- [6] CMS collaboration, D. Contardo, M. Klute, J. Mans, L. Silvestris and J. Butler, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, CERN-LHCC-2015-010, LHCC-P-008, CMS-TDR-15-02 (2015) 1.
- [7] CMS collaboration, A. Starodumov, P. Berger and M. Meinhard, *High rate capability and radiation tolerance of the PROC600 readout chip for the CMS pixel detector*, *JINST* **12** (2017) C01078.
- [8] L. Feld, M. Fleck, M. Friedrichs, R. Hensch, W. Karpinski, K. Klein et al., *A DC-DC conversion powering scheme for the CMS phase-1 pixel upgrade*, *JINST* **8** (2013) C02024.
- [9] J. Troska, S. Detraz, S. Seif El Nasr-Storey, P. Stejskal, C. Sigaud, C. Soos et al., *Prototype pixel optohybrid for the CMS phase 1 upgraded pixel detector*, *JINST* **7** (2012) C01113.
- [10] V. Veszpremi, *Performance verification of the CMS Phase 1 Upgrade pixel detector with collision data*, in *these proceedings*.
- [11] CMS Tracker Group, “<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2017>.”
- [12] CMS Tracker Group, “<https://twiki.cern.ch/twiki/bin/view/CMS/PixelOfflinePlotsAugust2017>.”