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Status of the CMS Phase 1 Pixel Upgrade

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Abstract

The silicon pixel detector is the innermost component of the CMS tracking system, providing high precision space point measurements of charged particle trajectories. Before 2018 the instantaneous luminosity of the LHC is expected to reach $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which will significantly increase the number of interactions per bunch crossing. The current pixel detector of CMS was not designed to work efficiently in such a high occupancy environment and will be degraded by substantial data-loss introduced by buffer filling in the analog Read-Out Chip (ROC) and effects of radiation damage in the sensors, built up over the operational period. To maintain a high tracking efficiency, CMS has planned to replace the current pixel system during "Phase 1" (2016/17) by a new lightweight detector, equipped with an additional 4th layer in the barrel, and one additional forward/backward disk. A new digital ROC has been designed, with increased buffers to minimize data-loss, and a digital read-out protocol to increase the read-out speed. Prototypes of digital single-chip modules have been characterized in a testbeam at DESY, before and after irradiation. Furthermore, energy calibrations using monochromatic X-rays were performed, and their dependence on irradiation and temperature were studied. This document will give an overview of the upgraded detector and will give a description of the module production of the 4th layer, which is being assembled and pre-tested by german institutes.

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Status of the CMS Phase 1 Pixel Upgrade

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The silicon pixel detector is the innermost component of the CMS tracking system, providing high precision space point measurements of charged particle trajectories. Before 2018 the instantaneous luminosity of the LHC is expected to reach $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which will significantly increase the number of interactions per bunch crossing. The current pixel detector of CMS was not designed to work efficiently in such a high occupancy environment and will be degraded by substantial data-loss introduced by buffer filling in the analog Read-Out Chip (ROC) and effects of radiation damage in the sensors, built up over the operational period. To maintain a high tracking efficiency, CMS has planned to replace the current pixel system during “Phase 1” (2016/17) by a new lightweight detector, equipped with an additional 4th layer in the barrel, and one additional forward/backward disk. A new digital ROC has been designed, with increased buffers to minimize data-loss, and a digital read-out protocol to increase the read-out speed. Prototypes of digital single-chip modules have been characterized in a testbeam at DESY, before and after irradiation. Furthermore, energy calibrations using monochromatic X-rays were performed, and their dependence on irradiation and temperature were studied. This document will give an overview of the upgraded detector and will give a description of the module production of the 4th layer, which is being assembled and pre-tested by german institutes.

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1. Introduction

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator currently in operation, providing the ability to answer the most fundamental questions in particle physics.

Until the end of 2012 the LHC delivered about $30\,\mathrm{fb}^{-1}$ of proton-proton collisions at center-of-mass energies of $\sqrt{s}$ = 7-8 TeV and a peak instantaneous luminosity of L_{inst}=$7.7\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The continuous ramp-up in instantaneous luminosity came at the price of a large number of multiple interactions per bunch crossing ("pile up") which posed several challenges to all LHC experiments, but in particular to the inner tracking detectors. Since the beginning of 2013 the LHC is in a long shut down (LS1) in order to prepare the machine for higher collision energies and larger luminosities.

The Compact Muon Solenoid (CMS) is one of the large-scale experiments at the LHC. It consists of an all-silicon tracker, an electromagnetic and hadronic calorimeter located inside a 3.8 Tesla solenoid magnet, and muon chambers interleaved with the return yoke. The CMS pixel detector is the innermost component of the CMS tracking system and plays a key role in the identification of primary and secondary vertices, quantities that are essential for the efficient identification of long lived particles, such as b-quarks, and for the search for new physics at the LHC. The presently installed three-layer system is designed to work well up to the design luminosity of L_{inst}=$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 25 ns bunch spacing.

However, thanks to the impressive performance of the LHC machine and its experiments, the current planning is that the design luminosity at 14 TeV center-of-mass energy is likely to be reached in 2015, and a luminosity twice as large is anticipated before 2018. After the second long shut down (LS2) in 2018, the LHC and its injector chains will be upgraded and even higher luminosities are expected.

At such running conditions the CMS pixel detector will suffer from inefficiencies due to dead time, tracking inefficiencies or higher fake rates, and effects of radiation damage built up over several years of operation. At twice the design luminosity and a bunch spacing of 25 ns (50 ns) the estimated inefficiency of the innermost layer is estimated to reach 16% (50%). It is therefore planned to replace the present pixel system during the winter technical stop of 2016/2017 with a new low mass detector, new digital read-out chips (ROCs) to minimize the data losses, and an additional space-point measurement to maintain high tracking performance in such high occupancy environment.

2. Phase-1 Upgrade Plans

The upgraded pixel detector will have four cylindrical barrel layers (BPIX) and three disks on either end of the barrel (FPIX). Simulations of a $\mathrm{t\bar{t}}$ sample with a pile up of 50 show that this will improve the tracking efficiency by up to 20%, while the fake rate is decreased by almost 20% at high pseudorapidities [1].

Even though the extra layer adds $\sim$50% more pixels, the total amount of material will be decreased by using ultra-light mechanical support structures, and by relocating electrical patch panels outside of the sensitive volume. Furthermore the cooling will switch from C_6F_{14} to a low-mass two-phase

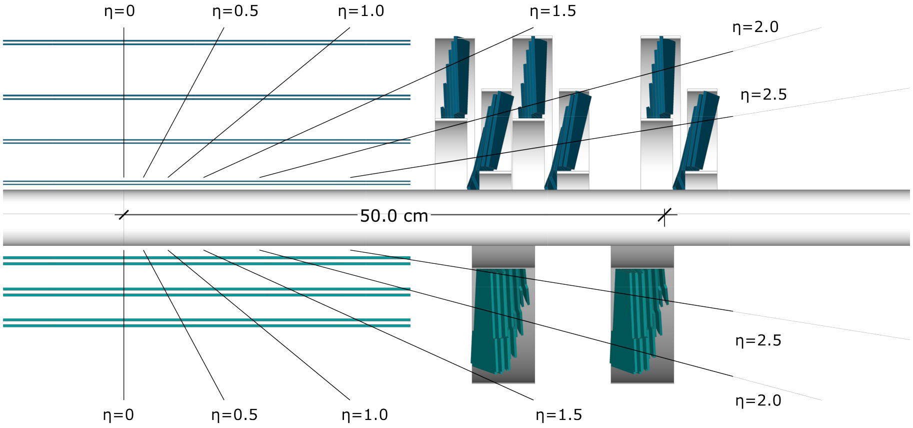

Figure 1: A comparison of the different layers and disks in the current (bottom) and upgrade pixel detectors (top). For the upgraded design, there are three end cap disks on each side, with each disk separated into an inner and outer ring. The inner ring is tilted at 12 degree towards the interaction point. The disks are positioned to maximize the four-hit coverage [1].

CO_2 cooling system, which will also allow to go to lower temperatures. A comparison to the presently installed three layer system is given in Figure 1.

The silicon sensors will keep the "n^+ in n" design of the present detector with $100 \times 150 \mu m^2$ pixel size, processed on 285 μm thick diffusion oxygenated float zone silicon. The pixels on the n-side are isolated with either moderated p-spray (BPIX) or p-stop (FPIX).

The basic architecture of the ROC also remains the same; 52 columns × 80 rows of pixels are bump bonded to the sensor. The read-out is organized in double columns, which operate independently. Zero suppressed hit information for pixels of two adjacent columns is stored in the same buffer at the periphery of the ROC. From there, hits corresponding to events verified by the CMS Level-1 trigger are read-out upon an external token passage.

The main data loss of the present pixel detector, if operated above the design luminosity, will be due to limited buffering, speed limitation in the transfer of hits from the pixels to the periphery and dead time of a double column while waiting for the read-out token. Major improvements for the current ROC design have therefore been developed:

- The new ROC will run internally with a 160 MHz clock instead of 40MHz. The output format will change from a multilevel encoded analog signal to a new digital read-out with a 160 Mbit/s LVDS data link.

- Major data loss will be avoided by increased time stamp and data buffers in the peripheries. In addition a new read-out buffer on the ROC will be added to buffer pixel hits, that were verified by the CMS trigger, until the external read-out token passage.

- Along with enhanced analog performance, namely reduced cross talk and time walk, a lower threshold will be reached (from approximately 3500 down to $\sim$1500 electrons).

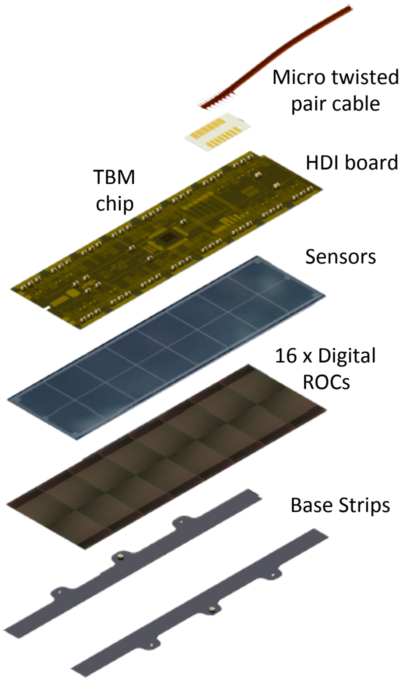

Figure 2: Components of the upgrade BPIX modules for layers 2 to 4 [1].

3. BPIX Modules

Each barrel layer consists of smaller components, called modules. An exploded view of a BPIX module is shown in Figure 2. A module for layers 2 to 4 consists of 16 read-out chips, bump bonded to a silicon sensor. Wirebond pads on the ROC peripheries extend 2 mm beyond the sensor, along the two long sides of the module. A high density interconnect (HDI) is glued on top of the sensor with wirebond pads to connect to the corresponding pads on the ROCs. Glued and wire-bonded on top of the HDI is the token bit manager chip (TBM). The TBM coordinates the read-out by issuing the read-out-token, and distributes external control signals via the HDI to the ROCs. Power and signal to the HDI are distributed by a single micro twisted pair cable. Each module will have 250 µm thick Si_3N_4 base-strips glued to the back side of the ROCs that permits mounting the modules on the mechanical support structure.

3.1 BPIX Module Production

Altogether 1216 modules plus spares have to be produced for the upgraded detector. This task is shared among different institutes from all over the world.

Layer	Radius [mm]	# Modules	Countries Involved
1	29	96	Switzerland
2	68	224	Switzerland
3	109	352	CERN, Finland, Italy, Taiwan
4	160	512	Germany

The fourth and biggest layer (512 modules plus ∼20% spares) will be built by German institutes. Half of them by the Karlsruhe Institute of Technology (KIT) and RWTH Aachen University and the other half by DESY and the University of Hamburg.

Once sensors and read-out chips are diced and under bump metallization (UBM) is applied, the module assembly procedure comprises a number of steps. The following will shortly describe the production steps in Hamburg.

DESY performs in-house bump-bonding to connect 16 ROCs to the sensor. This is done using a step motor controlled bump deposition machine from Pac Tech (SB2-Jet). Solder balls of 40 μm diameter made of SnAg are dropped though a capillary, molten by a laser and placed onto the bump pad of the sensors where they solidify. The step-motor is placing the solder balls with 5 Hz, which results in approximately 5 h bump deposition time per sensor. The sensor is then bonded onto the ROCs using a Finetech Femto flip-chip bonder, to form mechanical and electrical connection. Afterwards the so-called "bare module" is electrically tested to give feedback on the bump-bonding quality, and eventually bad modules are reworked by replacing individual chips. This is followed by gluing the base strips to the ROCs of the bare module. Afterwards the pre-assembled HDI is glued on the sensor side of the bare module and the electrical connection between HDI and ROC is formed with wire bonds. Each gluing step is performed on a separate jig that ensures to keep them in place with a vacuum hold until the glue has cured to ensure the exact placement of the parts.

At the end, the complete module undergoes final testing. This includes thermal cycling between room temperature and $-20\,^{\circ}$C and testing of its functionality under "high-rate" X-ray fluxes of up to 300 MHz/cm^2. In a last step a charge calibration of internal test pulses is performed (more on this in Section 4.2).

4. Testing of Prototype Modules

In order to test calibration procedures and influences of different parameters on the detector signal, so-called single-chip modules were extensively studied in several testbeams. Those single-chip modules consist of only a single ROC with the upgraded design, bump-bonded to a sensor and mounted on a printed circuit board (PCB). The read-out, clock and powering is then provided by a dedicated testboard.

4.1 DESY Testbeam Studies

The performance of the upgraded ROC was investigated in the DESY positron beam lines, which provide particles fluxes of $\mathcal{O}$(kHz/cm^2) with energies from 1-6 GeV. The single-chip modules were installed as a device-under-test (DUT) between the two arms of a EUDET/AIDA-family pixel beam telescope [2]. The DUT is rotatable, which allows to perform studies of column (turn) and row (tilt) pixel clusters, which simulates the Lorentz angle under which the charge carriers are deflected in the 3.8 Tesla magnetic field.

The telescope is composed of three upstream and three downstream planes with respect to the DUT, consisting of Mimosa26 Monolithic Active Pixel Sensors (MAPS) [3] devices. Triggering is provided by scintillators that are installed before and after the telescope planes.

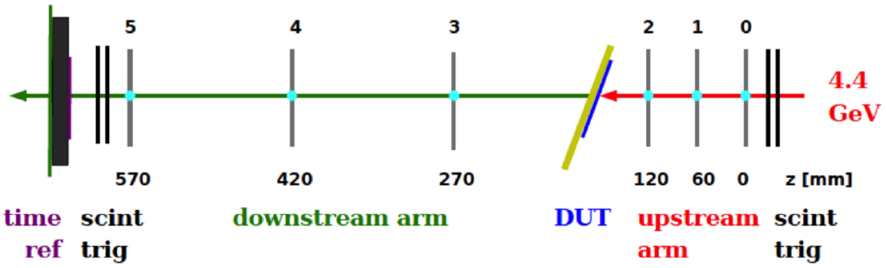

Figure 3: Diagram of the DESY testbeam setup using the EUDET pixel beam telescope.

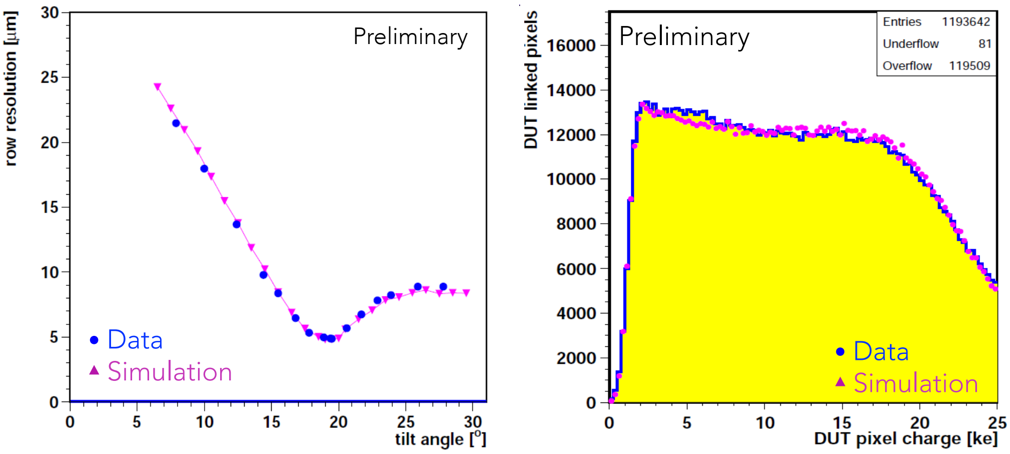

Figure 4: Left shows the row resolution versus tilt angle, right shows the cluster charge at the optimal angle of 19.5°. Data is plotted in blue and simulation in pink.

Since the Mimosa26 read-out integrates over a long time period $\mathcal{O}$(100µs) another CMS pixel detector is mounted at the end to provide a timing reference [5]. The arrangement of the testbeam setup is shown in Figure 3.

The row resolution, corrected for the telescope resolution, versus the tilt angle is shown on the left side of Figure 4. It is clearly visible that the best result of ∼5.1 µm is achieved at a tilt angle of 19.5°. At this angle the charge, produced by an incident particle, is exactly shared among two pixel rows. The right plot shows the pixel charge distribution at this optimal angle, showing a “turn on” at a threshold of approximately 1500 electrons. The test-beam data could be veryfied by simulation (plotted in pink) based on the CMS package PixelAv [6].

In order to investigate the radiation hardness of sensor and ROC, the same single-chip module was irradiated at the CERN PS with 23 GeV protons to 130 kGy, which corresponds to the expected lifetime dose of the fourth barrel layer, and measured again in the DESY testbeam. Figure 5 shows the spatial resolution at the optimal tilt angle. After subtracting the intrinsic telescope resolution of 4.2 µm the spatial resolution is only slightly degraded to a value of 6.2 µm .

4.2 X-Ray Studies

To perform tests and calibrations of the read-out chain, the ROC features the possibility to inject an adjustable amount of charge at the input of the amplifying circuitry of every pixel [7].

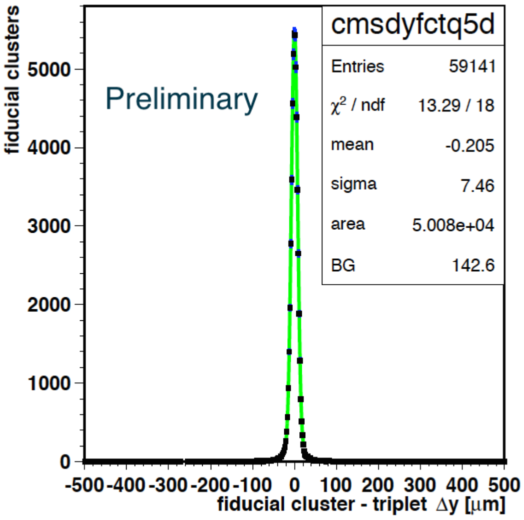

Figure 5: Spatial resolution in 100 μm (row) direction of the pixels after the expected full fourth layer lifetime dose of 130 kGy. The resolution is calculated as the distance (Δy) between the track measured in the upstream telescope triplet, and the CMS signal in the fiducial region of sensor.

The amount of charge that is injected is regulated through a settable voltage of a digital-to-analog converter (DAC), called `VCal`. Since this calibration signal is also used to set the thresholds of each pixel it is therefore important to establish a relation between the `VCal` units and the corresponding amount of charge seen by the pixel[1]. This calibration is performed by comparing the amplitude of test pulses to a well defined amount of charge generated in the sensor by photon absorption, using the K_α lines of different elements. The University of Hamburg uses a primary beam of X-ray photons coming from a tungsten tube with a maximum of 35 keV accelerating voltage (the other production centers use similar setups). The primary beam hits a rotatable cube with different fluorescent materials (Cu, Ag, Mo, Te) to get a monochromatic X-ray beam of a well defined energy. By measuring the detector signals from these target materials, the calibration curve can be determined. This curve relates the detector input, i.e. the charge generated in the sensor by photon absorption, to the measured signal in the detector.

Figure 6 (left) shows a picture of the setup used in Hamburg. The right side shows an example calibration curve measured with four different targets. The parameters of a linear fit can be used to relate the `VCal` test pulse units to the collected charge. Several single-chip prototypes have been studied, and detailed studies of the influences of different experimental parameters such as irradiation rate and temperature on the detector signal and on the resulting calibration curves have been performed. The slope of the relation was found to be relatively stable around $50 \pm 5\ e^-$/`VCal`. As mentioned in 3.1, this calibration is also part of the module production qualification, and is the first time the full modules are tested with real particle fluxes. In addition, for performing "high-rate" test the modules are exposed to the direct beam of the tungsten tube.

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[1] Even though the pixel detector is not directly used for energy measurements, the calibration is necessary since charge sharing is exploited for improving the spatial resolution [4].

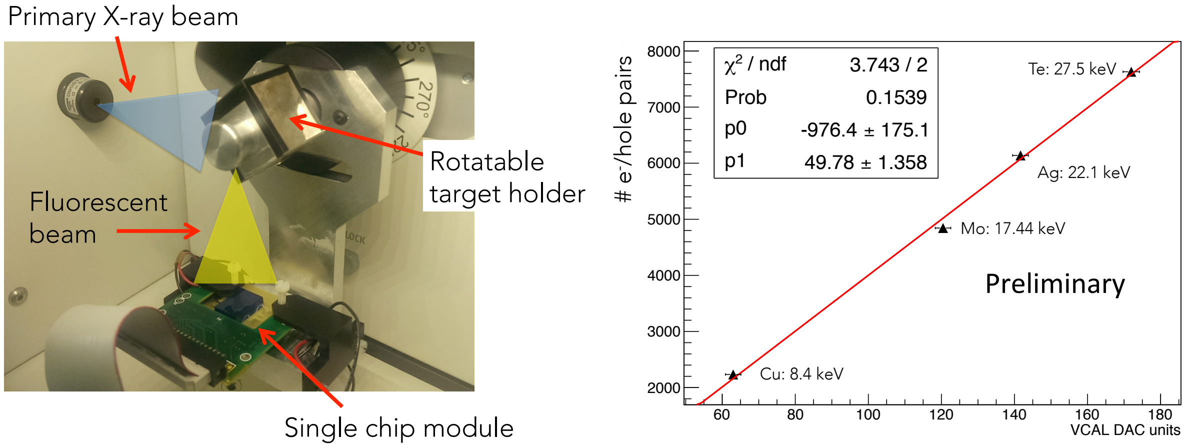

Figure 6: Energy charge calibration of internal test-pulses. The setup used in Hamburg (left), example calibration line using different fluorescent targets (right). The X-axis show the recorded DAC counts in VCal units, the y-axis shows the number of electron/hole pairs produced in Si, based on literature values of the corresponding K_α transition energies.

5. Conclusion

In order to cope with the foreseen increase in instantaneous luminosity and pile-up at the LHC, CMS will replace the entire pixel detector during the extended technical stop in 2016/2017. The upgraded detector will have an additional layer, reduced material budget and a new digital read-out chip with larger buffering capabilities. These upgrades will maintain or even improve the high tracking efficiency of the presently installed system at luminosities of up to $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and pile-up exceeding 50. Preliminary measurements of prototype modules demonstrate the improvement of the new ROC design. After being irradiated to the full lifetime dose of the outermost layer, the chip remained fully efficient and its spatial resolution was only slightly decreased. The BPIX module production, which is shared among different institutes, is well advanced. The sensors are produced, the final ROC submission is imminent and all production centers successfully assembled bare modules with excellent quality. Start of the mass production is scheduled for fall 2014.

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