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The CMS pixel detector and challenges (prospectives) for its upgrade

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Abstract

The CMS pixel detector was installed in July 2008 in the innermost region of CMS. It consists of 66 million pixels of 100μm by 150μm size over 3 barrel layers and 2 forward disks. The pixel system has been successfully commissioned. Over 80K muon tracks were taken during the CMS cosmic runs and the detector is ready for the first physics run. The pixel detector, so close to the interaction point, will be exposed to a very high radiation dose. The estimation is that the first barrel layer, located at 4.3 cm from the beam pipe, after 3 years of LHC running at full luminosity will become inefficient for position resolution reconstruction. For this reason, a susbstitution of a new pixel detector in 2014 has been already scheduled. At the same time an LHC luminosity upgrade is also planned. While a simple rebuild of the current detector could be done, the expectation is to design a new one, optimized for higher luminosity. This paper describes the present system and its performance as well as possible solutions for the upgrade.

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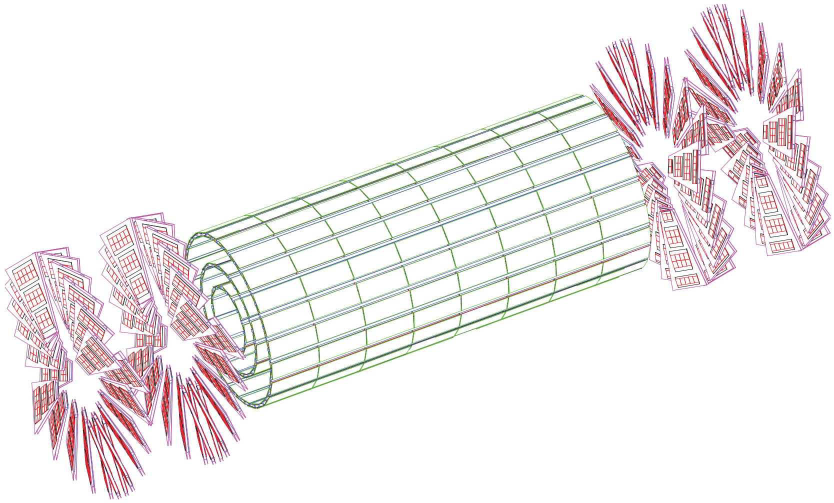

Figure 1: Layout of the CMS pixel detector with three barrel layers and 2 disks on each side.

1 The CMS pixel detector

The CMS detector is one of the large general purpose detectors in the Large Hadron Collider located near Geneva, Switzerland [1]. Expectations are that proton-proton collisions will occur at a center of mass energy of 14 TeV and design luminosity of 10^{34} cm^{-2}s^{-1}. The central tracking system for the CMS detector includes silicon strip detectors and pixel detectors which are inside of a solenoidal magnetic field of approximately 4 Tesla. The CMS pixel detector resides in the centermost part of the detector. It consists of a three layer barrel detector with a length of 56 cm and two disks at $z = \pm 34.5$ and $z = \pm 46.5$ cm on each side of the interaction region. Figure 1 shows the geometry where the innermost barrel resides at 4.3 cm from the interaction point. The pixels have a size of $100\ \mu\mathrm{m} \times 150\ \mu\mathrm{m}$. There are approximately 66 million pixels in the system[2].

After both the barrel and forward pixel detectors were installed inside of CMS in July, 2008, commissioning has been ongoing[3]. CMS collected a total of 370 million cosmic ray events in the Fall of 2008. For this run, 99.1% of the barrel channels and 94% of the disk channels were working and over 80,000 tracks were constructed with pixel hits. Figure 2 shows the hit exposure of the detector. Less than 0.00056% of the pixels were declared noisy and were masked during the run.

Operational parameters were studied including gains and thresholds. The signal to noise ratio is good with a minimum ionizing particle depositing about 22,000 electrons. For the barrel section, typical noise values are around 140 electrons while for forward disks, there is about 80 electrons in noise. Figure 3 shows the distributions of the thresholds and pixel noise.

The Lorentz angle can be measured by looking at the spread of the charge drift distribution as a function of the track incidence angle and finding the minimum. Figure 4 shows these measurements for magnetic fields of zero and 3.8 T. At 3.8T, the angle was found to be about 24.7° for the barrel detectors and about 4.0° for the endcaps. An initial alignment procedure was performed. There were 37,000 tracks with a transverse momentum greater than 20 GeV/c. The pixel hit efficiency was found to be greater than 96%. Initial barrel position resolutions have been found in a module to be approximately 20 microns in X and 30 microns in Y.

After the cosmic run, the forward disk pixel systems were removed to recover channels and improve cooling. The cooling plant was refurbished and commissioning resumed in April, 2009 for the pixel detectors. The detectors will be ready for beam starting in the Fall of 2009.

As the pixel layers are very close to the interaction point, they will have to endure high particle fluences. The pixel detector has been designed to withstand a fluence up to $6 \times 10^{14} n_{eq}/\mathrm{cm}^2$. This fluence corresponds to a lifetime of approximately two years of design luminosity running of the LHC at $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$[4]. Expectations are that the track resolution and the efficiency of the detector will degrade slowly with irradiation.

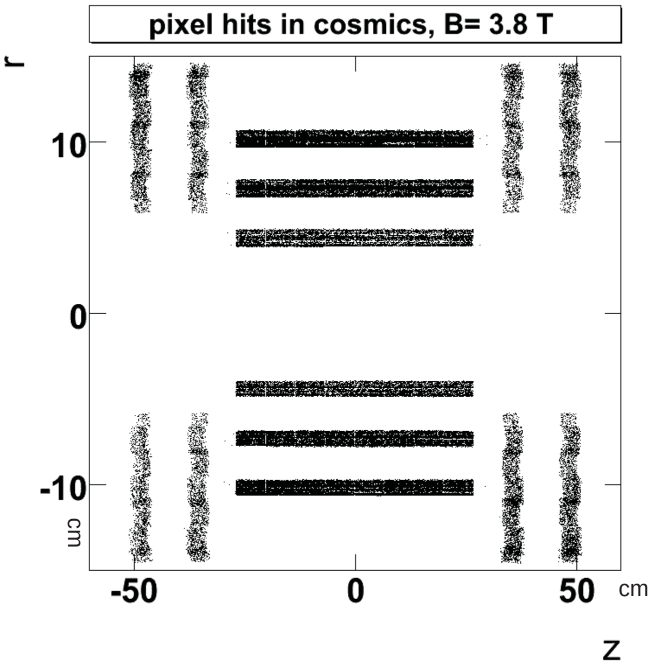

Figure 2: Transverse view of hits obtained from cosmic tracks during the cosmic data run in Fall 2008.

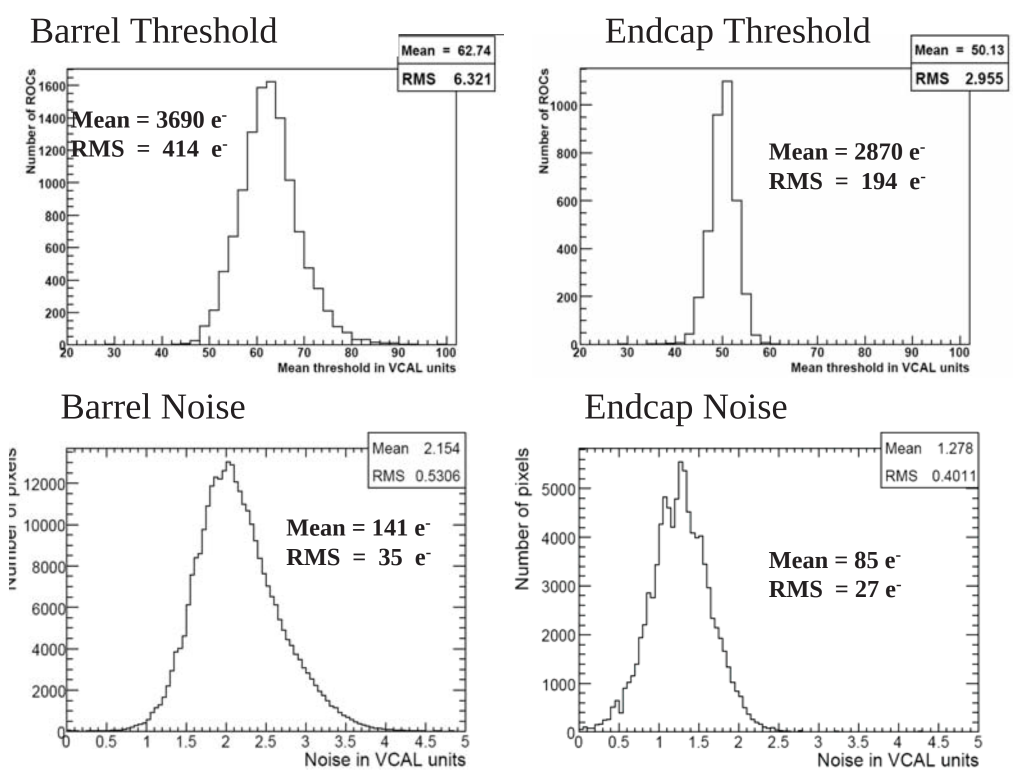

Figure 3: Threshold (top plots) and Noise (bottom plots) distributions for the barrel (left) and endcap (right) detectors.

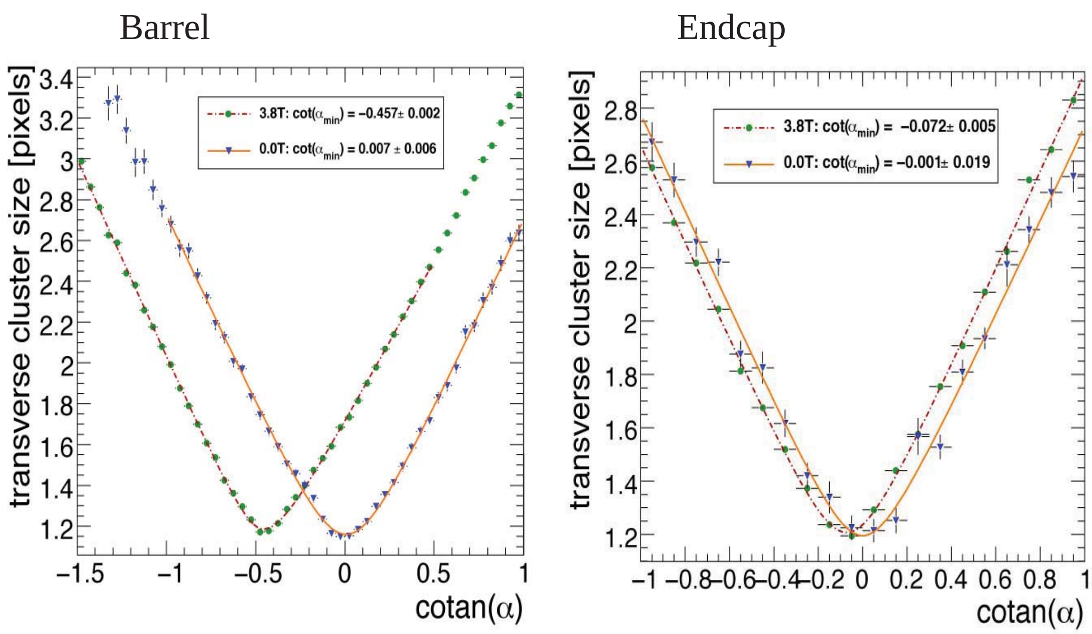

Figure 4: Transverse cluster size as a function of the track incident angle (α) measured at both zero and 3.8T for the barrel (left) and endcap (right) detectors.

2 Upgrade plans

The LHC is expected to take data for several years and be upgraded in two phases eventually reaching an expected instantaneous luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ towards the end of the next decade. The initial phase upgrade shutdown is expected around 2014 with the target luminosity for this Phase I being $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Radiation damage concerns imply that greater than 50% of the pixel barrel modules would have to be replaced within a couple of years of running. The readout chip for the detector also becomes inefficient at high rates due to buffer limitations and dead times during data transfer. There is also substantial material in the entire tracking system. The total amount of material in the pixel detector, including the supply tubes with auxiliary electronics and the endcaps, is up to 30 – 40 % of a radiation length for the forward region, which is still inside the acceptance of the CMS tracker. Figure 5 shows where these support services are located.

A plan has been developed to replace the entire pixel detector for Phase I. As the time scale for producing the detector as well as commissioning the detector after it is installed is not long, a complete redesign is not called for. Reusing as much of the readout chain as possible is desirable. With this new detector, the material can be substantially reduced and more layers can be added. There will be four barrel layers and three disks on each side. This will allow one to have three pixel layers hit over almost the full detector coverage area. Adding a fourth layer at a radius of 16 cm also allows a smaller extrapolation uncertainty between the pixel track segments and the strip tracker segments which have the innermost layer at 25.5 cm. The upgraded detector must re-use the existing cooling, power, and readout services.

The design calls for ultra light mechanics to reduce the material which will include CO_2 cooling instead of the present C_6F_{14} system. To stay within the existing cables, the readout will switch from 40 MHz analog to 320 MHz digital. The barrel will contain 1428 identical modules with the inner layer at 3.9cm and the outer layer at 16.0cm. Material will be reduced in the module, but the geometry and parts are the same as the current barrel pixel detector. The three disks per side will have 116 modules/disk using a similar module design to the barrel which has 16 readout chips. The blade geometry allows for charge sharing. The new layout of the CMS pixel detector is shown in Figure 6. The new mechanical structures reduce the material per layer in the central region by a factor of three so that even with the fourth layer included, the total material is less than $1/2$ of the existing system.

The sensors for the current pixel detector are made of n substrates with n+ implants. The barrel-type pixel sensors with their readout chips have been exposed to radiation fluences up to $5 \times 10^{15} n_{eq}/cm^2$[5]. The charge collection efficiencies have been measured and there is sufficient charge to use them up to approximately $3 \times 10^{15} n_{eq}/cm^2$ which is above the design request to survive to a fluence of $6 \times 10^{14} n_{eq}/cm^2$. Particles have also been detected at

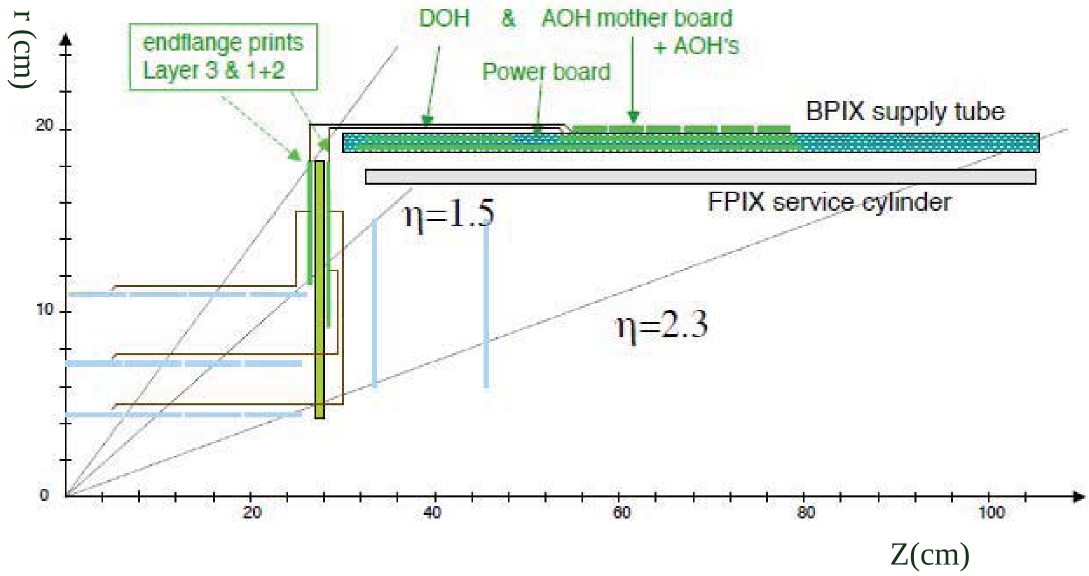

Figure 5: Diagram showing the location of material components in active area of the present CMS pixel detector.

the highest fluences but more study is needed. The operation voltage needed increases to about 1000 Volts at the highest fluences. Studies are ongoing to decide whether modifications are needed to these sensors for use in the Phase I upgrade.

The current readout chip is the PSI46 chip made in the 0.25μm process which reads out 52 by 80 pixels. The module transmits pulse-height information and analog coded pixel addresses at 40 MHz to an analog optical hybrid. Optical fibers connect to this hybrid and transmit the signals to a front end driver board situated in the readout crates. The number of optical fibers is constrained by space limitations and they will not be replaced for the upgrade. An increased bandwidth transmitted per fiber is needed as there are approximately 60% more modules. The plan is to switch from analog to a more robust signal by providing digital transmission with one link of 320 Mbit/s per module. Presently, there are two optical fibers per module for the first two layers of the barrel system.

Care has been taken to change as few components as possible. The readout chip, module controller chip (TBM), and the receivers for the front end electronics boards will change. The control and monitoring electronics will not change. This part of the system includes the fast control links at 40 MHz, the trigger, and the fast I^2C communications.

For the PSI46 chip, the address treatment is digital already with the analog signals being generated with a digital-to-analog converter which will no longer be needed. However, an 8-bit ADC will be added for the analog pulse height information. More data buffers are needed to accomodate the higher occupancies expected with the increased luminosity. Digital drivers running at a rate of 160 MHz will also be added. A slightly larger chip is easily accomodated with the present module design. Prototype components have been tested for a 4-bit ADC and a phase lock loop needed to derive the 160 MHz clock from the 40 MHz LHC clock with a test chip submission in a 0.25μm CMOS process.

The module controller TBM chip will need to be modified to multiplex the data streams from the readout chips onto a single 320 MHz link. With this scheme, the time required to transmit the digital data is the same as that to transmit analog data at 40 MHz.

In addition to the material reduction from the mechanical structure design and CO_2 cooling, a new cabling scheme to the optical hybrid board will reduce the material further. Currently, there are kapton cables that connect the module to an endprint electronics board. Then another kapton cable connects this endprint board with the optical hybrid board located close on the barrel support tube directly outside of the forward disks. The plan is to eliminate the endprint and move the optical hybrid boards out of the active area, by using 2 meter long micro-twisted pair readout cables. The characteristics of these 125μm diameter cables have been studied and no additional electrical shield will be needed.

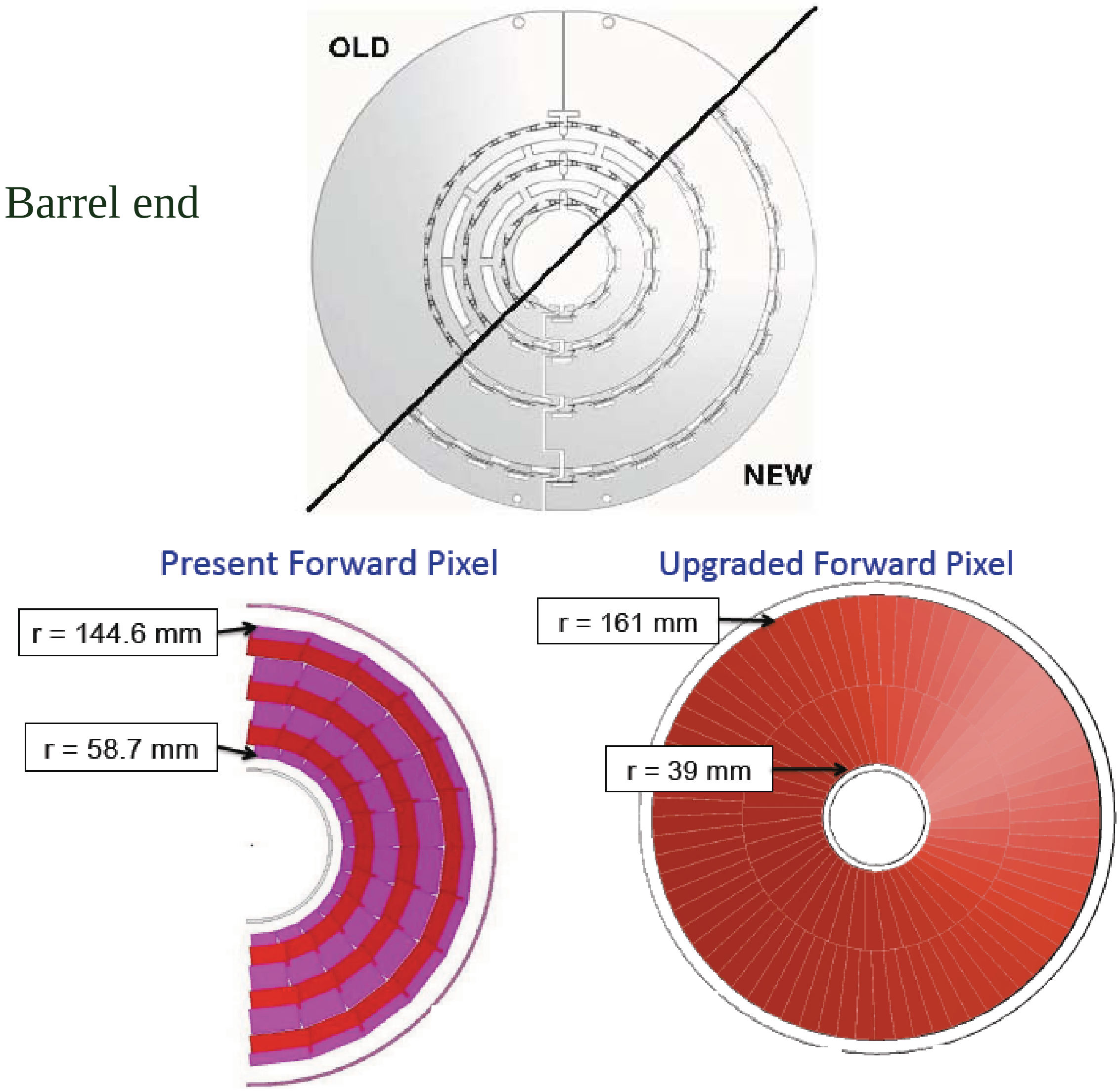

Figure 6: Mechanical layouts shown for: the barrel old and new (left), the present (center) and proposed (right) forward pixel disk.

Power considerations are an issue so low power operating links have been prototyped that operate using a differential voltage level of only 20mV. These have been found to consume only 1.2 mW per link[6]. The power supplies will also need to have their operating parameters adjusted. There will be new digital optical receivers needed to read out the signals from the fibers on the VME FED board. A new daughtercard is being prototyped.

3 Conclusions

In summary, the CMS pixel detector has been successfully installed and commissioning is proceeding. The operational parameters have been studied during a cosmic ray run and the detector is performing well and ready to begin to take beam data in the Fall of 2009. The design is underway for an upgraded pixel detector with four barrel layers and 3 disks on each end for installation for the Phase I LHC upgrade expected around 2014. This new detector will have substantially reduced material and will enhance the robustness and efficiency of tracking.

Acknowledgement

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References

[1] The CMS Collaboration, The CMS experiment at the CERN LHC, Journal of Instrumentation 3 S08004 (2008) 26–89, http://www.iop.org/EJ/journal/-page=extra.lhc/jinst.

[2] D. Kotlinski, Status of the cms pixel detector, JINST 4 P03019.

[3] L. Caminada, A. Starodumov, Building and commissioning of the CMS pixel barrel detector, JINST 4 P03017.

[4] The CMS Collaboration, CMS Tracker, Technical Design Report LHCC 98-6, CERN, Geneva, Switzerland (1998).

[5] T. Rohe, et al., Radiation hardness of cms pixel modules, these proceedings.

[6] B. Meier, Design studies of a low power serial data link for possible upgrade of the cms pixel detector, cERN-2008-008 (2008).