Available on CMS information server

CMS CR-2008/087

The Compact Muon Solenoid Experiment

Conference Report

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

07 November 2008

Overview of the CMS Pixel Detector

Giuseppe B. Cerati, Università degli Studi di Milano-Bicocca and I.N.F.N., on behalf of the CMS collaboration

Abstract

The Compact Muon Solenoid Experiment (CMS) will start taking data at the Large Hadron Collider (LHC) in 2009. It will investigate the proton-proton collisions at $14\ TeV$. A robust tracking combined with a precise vertex reconstruction is crucial to address the physics challenge of proton collisions at this energy. To this extent an all-silicon tracking system with very fine granularity has been built and now is in the final commissioning phase. It represents the largest silicon tracking detector ever built. The system is composed by an outer part, made of micro-strip detectors, and an inner one, made of pixel detectors. The pixel detector consists of three pixel barrel layers and two forward disks at each side of the interaction region. Each pixel sensor, both for the barrel and forward detectors, has $100 \times 150\ \mu m^2$ cells for a total of 66 million pixels covering a total area of about $1\ m^2$. The pixel detector will play a crucial role in the pattern recognition and the track reconstruction both in the offline analysis and online high-level trigger.

Presented at *2008 IEEE Nuclear Science Symposium and Medical Imaging Conference and 16th International Workshop on Room Temperature Semiconductor Detectors,19 - 25 October 2008,Dresden,Germany,14/11/2008*

1 Introduction

The Compact Muon Solenoid[1] is the general purpose experiment installed at Point 5 of the Large Hadron Collider (P5); it is currently under commissioning and waiting for the first beam collisions foreseen in 2009. Its main design feature is the large aperture superconducting solenoid which is operated at $3.8\ T$ and fully contains all the tracking and calorimetric systems. In the center of the apparatus the two proton beams collide with a center of mass energy of $14\ TeV$, a frequency of $40\ MHz$ and up to a luminosity of $10^{34}\ cm^{-2}s^{-1}$. The pixel detector is the device closest to the interaction point and constitutes the key detector for high performance tracking. It has to provide a robust seeding for the track pattern-recognition, and an accurate measurement of the track impact-parameter, reconstruct primary and secondary vertices, identify jets from b quarks and perform fast tracking and vertexing at trigger level. In addition, the pixel system has to operate with excellent performance in a very hostile environment where the expected radiation fluence at $r = 4\ cm$ from the beam axis is $3 \cdot 10^{14}\ n_{eq}cm^{-2}$ per year[1)].

2 Detector Description

The CMS pixel detector covers a pseudorapidity range $-2.5{<}\eta{<}2.5$ (Fig. 1), matching the acceptance of the strip tracker. The pixel cell size of $100 \times 150\ \mu m^2$ has been chosen to provide high-resolution 3D space points close to the interaction point for precise vertex determination and fine granularity for charged track pattern recognition. It consists of three barrel layers (BPix) with two end-cap disks (FPix) on each side of the barrel as shown in Fig. 2. The $53\ cm$ long BPix layers are located at mean radii of 4.4, 7.3, and $10.2\ cm$. The FPix disks (Fig. 3) extending from 6.1 to $15.0\ cm$ in radius are placed on each side at $z = \pm 34.5\ cm$ and $z = \pm 46.5\ cm$. Bpix (Fpix) contain 48 million (18 million) pixels covering a total area of 0.78 (0.28)m^2.

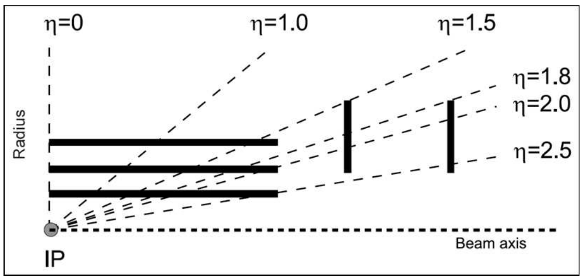

Figure 1: Pseudorapidity coverage of the pixel system.

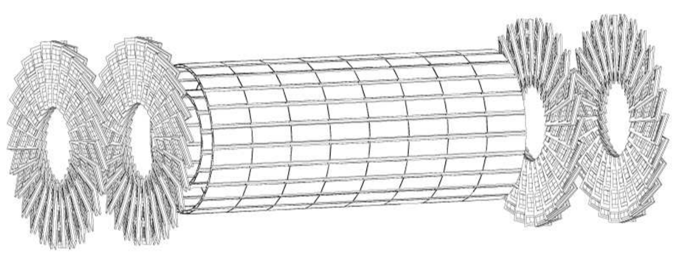

Figure 2: Schematic view of the CMS pixel system.

The Lorentz drift of the electrons inside the magnetic field of $3.8\ T$ leads to charge spreading of the order of $150\ \mu m$ for unirradiated sensors $\sim 270 \mu m$ thick. Therefore the charge will be collected in more than one pixel. Charge interpolation leads to an improved spatial resolution. The forward detectors are tilted at $20°$ in a turbine-like geometry to induce charge sharing so that the drift direction is not parallel to the magnetic field. A position resolution of approximately $10\ \mu m$ in both directions can be achieved with charge sharing between neighboring pixels.

The sensors are n-on-n with n^+ implants on n bulk silicon. The fabrication of n-on-n sensors is complex and requires inter-pixel isolation since n-type implants are shorted by the accumulation layer at the Si-SiO_2 interface. BPix and FPix have adopted a moderated p-spray and optimized p-stop isolation, respectively. Sensors are connected to the read out chips with indium (barrel) and lead-tin (forward) bump bonding.

The ROC[4] has been designed at Paul Scherrer Institute (Zurich) with a $0.25\ \mu m$ CMOS radiation hard technology.

[1)] n_{eq} stays for $1\ MeV$ neutron equivalent.

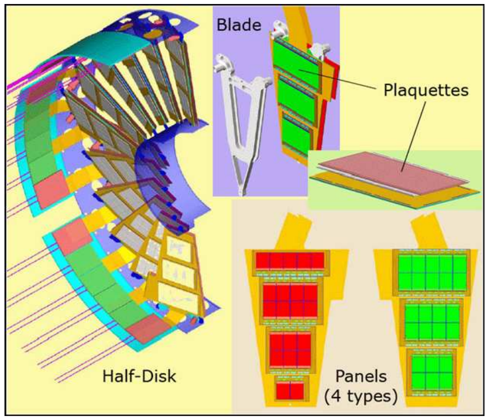

Figure 3: Main components of the forward detector: a half disk, a blade and two panels with the five types of unit modules (plaquettes).

Each ROC provides an analog readout with zero suppression of a 52×80 pixel-matrix, organized in 26 double-columns. The pixel-cell address is coded on six discrete levels as shown in Fig. 4. The readout of all the ROCs of a pixel module (Bpix) or of several plaquettes on a panel (Fpix) is controlled by the token bit manager chip (TBM). For each CMS Level 1 trigger, the TBM generates a token bit that is sent to the ROCs; one ROC at a time transmits its hit information back to the TBM, which, in turn, sends it to the Front End Driver boards (FED).

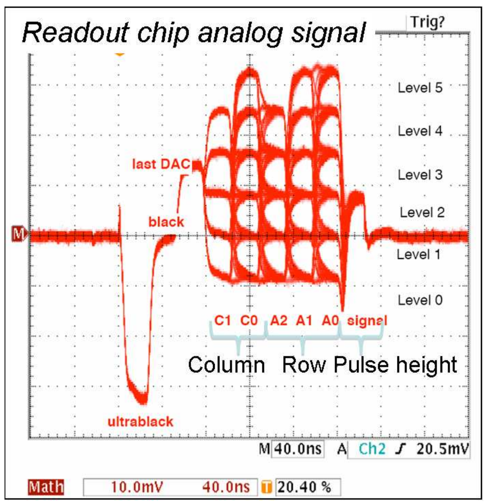

Figure 4: Readout chip analog signal. Seven discrete levels (six adress levels and one ultrablack) and one continuos pulse height signal are visible.

3 Test Beams

Test beams have been carried out separately for Bpix[5] and Fpix[8] modules to measure their performance and radiation toleance.

The barrel modules were first tested in a high rate $300\ MeV/c$ pion beam at PSI and then at the H2 beam line of the CERN SPS in a $3\ T$ magnetic field. The measured detection inefficiency is $\simeq 0.1\%$ for unirradiated sensor with an applied threshold of 2,000 electrons. After a fluence of $\Phi = 6 \cdot 10^{14}\ n_{eq}cm^{-2}$ the inefficiency remains below 2% and the collected charge is $> 60\%$ of the released charge for $V_{bias} > 400\ V$. The position resolution for perpendicular tracks and clusters of two pixels is $\sigma \simeq 7\ \mu m$ along the Lorentz shift coordinate. This precision can be achieved also after irradiation applying η-correction to the reconstructed position. For clusters of a single pixel the residual distribution has RMS of $20\ \mu m$ and $25\ \mu m$ for unirradiated and irradiated sensors respectively.

Forward pixel modules have been irradiated at the Indiana University Cyclotron Facility using a $200\ MeV$ proton beam. During the irradiation, the beam was centered on one edge of the plaquette to produce a highly non-uniform dose profile similar to that expected in CMS. The irradiation beam was roughly Gaussian in shape with $\sigma \sim 2\ cm$

and $1.6 \cdot 10^{15}\ n_{eq} cm^{-2}$ peak-fluence. These detectors were then operated in a $120\ GeV$ proton beam at Fermilab. The results from this beam test showed that the irradiated sensors still collect $\sim 75\%$ of the released charge, have a breakdown voltage well above $600\ V$ and a detection efficiency at the level of $\sim 99\%$.

4 Physics Performance

The pixel detector is fundamental for the track reconstruction process[2] for several reasons. First of all, seeds of three pixel hits or, alternatively, two pixel hits plus the beam constraint, are used to initiate the main track pattern recognition process. This pixel-only seeding is fully efficient up to $|\eta| < 2.4$. For higher η-values and up to $\eta = 2.5$ a mixed pixel-strip seeding is necessary. The high position-resolution provided by the pixel detector allows for an impact-parameter resolution of about $10\ \mu m$ for high momentum tracks as shown in Fig. 5, where the resolution for single muons with $p_T = 1$, 10 and $100\ GeV/c$ is reported.

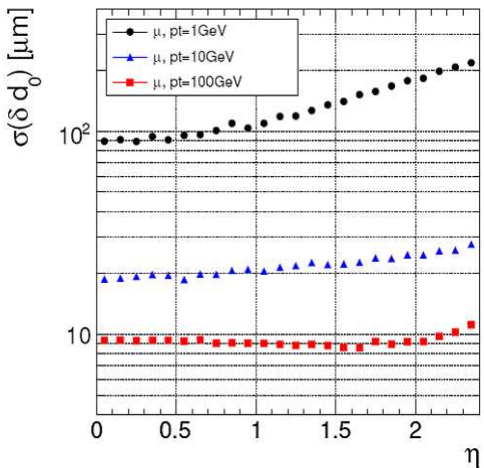

Figure 5: Transverse impact parameter resolution for single muon tracks reconstructed in the whole CMS tracker (pixels and strips). The resolution is of the order of $10\ \mu m$ for $p_T \geq 10\ GeV/c$, while it degrades to $\sim 100\ \mu m$ for low p_T tracks.

The pixel detector also allows for a standalone track and vertex reconstruction[3], which is performed in the High Level Trigger. Obviously, in this case only tracks having three pixel hits can be reconstructed. The efficiency for these tracks is about 99% for $p_T \geq 3\ GeV/c$ (see Fig. 6). The impact parameter resolution is $\sim 80\ \mu m$ for $p_T \geq 6\ GeV/c$. The associated momentum resolution, limited by the short pixel lever arm, is better than 20% up to $p_T \leq 10\ GeV/c$. For $p_T = 1\ GeV/c$ tracks, in particular, the momentum resolution is about 7%.

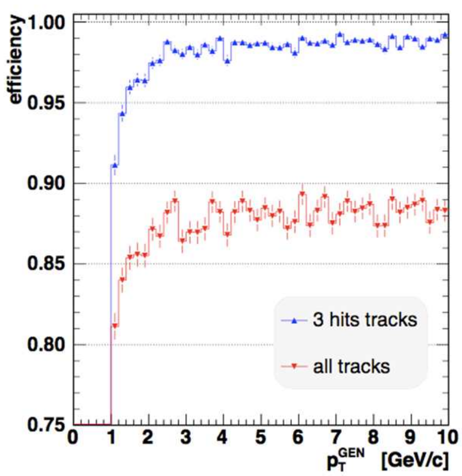

Figure 6: Efficiency for the track triplet finding: three hit tracks (blue) and all track (red) efficiency measured for single muon events. The first corresponds to the algorithmic efficiency, the latter to the global efficiency including detector data loss.

5 Commissioning and Installation

The preliminary commissioning of the pixel detector prior to the installation at P5 has been completed. The barrel sectors have been separately tested at PSI, assembled and then shipped to CERN. The forward disks have been characterized and assembled at Fermilab, and then shipped to CERN. At the CERN Tracker Integration Facility[6] they have been re-assembled and throughly tested with an experiment-like readout system. The main calibration tests performed have been the following ones[7]:

- ”Address Level Calibration”, to establish a minimal safe separation among the six discrete levels, typically better than 20σ;
- ”Pixel Alive”, to check if the single pixel-cell responds in the proper way to a charge injection. The result is a map of active and dead cells (see Fig. 7);
- ”S-curve”, to measure threshold and noise of each cell by analyzing the response efficiency curve at increasing injected charge values (Fig. 8);
- ”Gain Calibration”, to improve the linearity of the gain curve in the low signal region and to measure the resulting fit parameters.

The resulting performance of the pixel detector is excellent. The mean noise value, indeed, is lower than 120 electrons, while the number of noisy and dead cells are $< 0.014\%$ and $< 0.04\%$ respectively. A linear gain response has been established up to 24000 electrons. This will be extended to 33000 electrons, i.e. 1.5 MIP, in the final commissioning at P5.

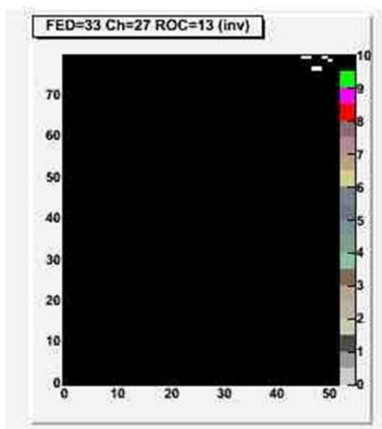

Figure 7: Example of *Pixel Alive* test for one ROC. The black cloured cells have a 100% response efficiency, while the white 0%.

The barrel and forward pixel detectors have been installed in CMS on 23-24 July and 29-31 July 2008 respectively. Despite the small amount of time granted for these operations, the pixel detectors have been successfully inserted in CMS. Only $\sim$5 Fpix blades have been lost during the installation for problems of power supply. The resulting situation is that 99% of the barrel and 94% of the forward detector are perfectly working.

The final phase of the commissioning has already started. The pixel system has successfully joined the CMS global runs with cosmic rays and the first tracks with hits in pixel detector have been observed. An event display with a cosmic track crossing all the CMS apparatus including the pixel detector is shown in Fig. 9. A fine tuning of the calibration parameters is still ongoing to achieve the best performance. The next shutdown will be useful to recover the few blades lost during the installation.

6 Conclusions

After long design and construction efforts, the CMS pixel detector is now installed and operational within the CMS experiment. It is ready for the first beam collisions and physics.

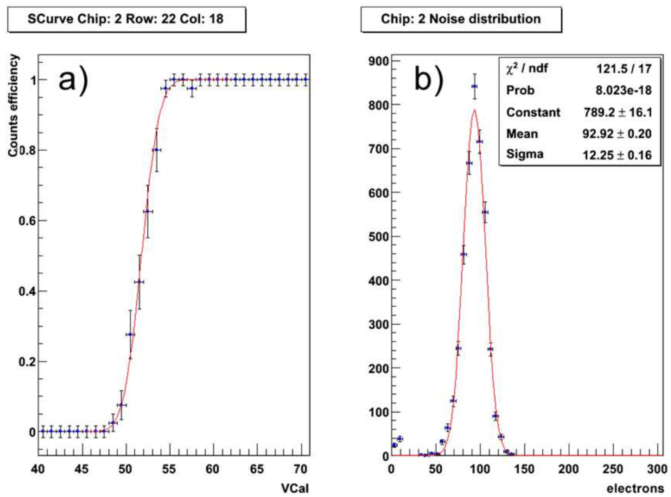

Figure 8: Example of threshold and noise measurement. a) S-curve for one pixel cell; b) noise distribution for the pixels in a single ROC.

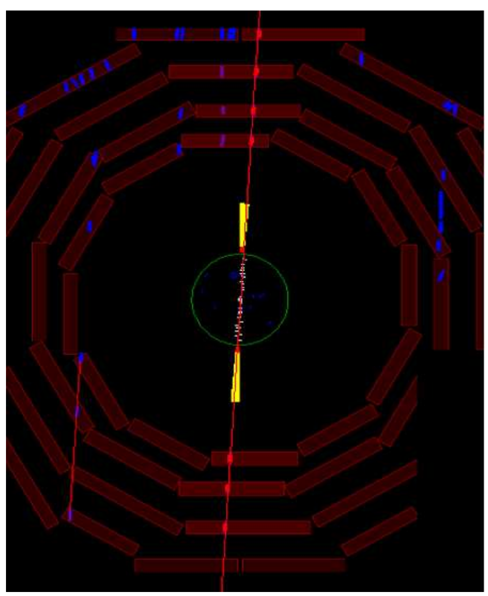

Figure 9: Event display with a cosmic track in the CMS apparatus with zero magnetic field. The pixel hits are the innermost white points.

Acknowledgment

The author would like to thank the CMS pixel collaboration and in particular the Milano-Bicocca CMS pixel group. A special thank to Luigi Moroni and Mauro Dinardo for the precious help.

References

[1] R. Adolphi et al., *The CMS experiment at the CERN-LHC*, JINST 3:S08004, 2008.

[2] CMS Collaboration, *CMS Physics TDR Volume 1*, CERN-LHCC-2006-001 (2006).

[3] S. Cucciarelli, M. Konecki, D. Kotlinski, T. Todorov, *Track reconstruction, primary vertex finding and seed generation in the Pixel Detector*, CMS NOTE 2006/026.

[4] H. C. Kastli et al., *Design and performance of the CMS pixel detector readout chip*, Nucl.Instrum.Meth.A565:188-194,2006.

[5] Y. Allkofer et al., *Design and performance of the silicon sensors for the CMS barrel pixel detector*, Nucl.Instrum.Meth.A584:25-41,2008.

[6] M. Dinardo, *CMS Pixel commissioning*, Proceedings of Science (Vertex 2007 16th International Workshop on Vertex detectors, September 23-28, 2007, Lake Placid, NY, USA).

[7] D. Menasce, M. Turqueti, L. Uplegger, *The Renaissance: A test-stand for the Forward CMS Pixel Tracker Assembly*, Nucl.Instrum.Meth.A579:1141-1149,2007.

[8] G.B. Cerati et al., *Radiation tolarance of the CMS Forward Pixel-Detectors*, to be submitted to Nucl.Instrum.Meth.A.