FERMILAB-CONF-08-565-E

Commissioning of The CMS Forward Pixel Detector

Ashish Kumar (for the CMS Forward Pixel Collaboration)
The State University of New York at Buffalo,
Buffalo, NY 14260, USA
E-mail: ashish@cern.ch

ABSTRACT: The Compact Muon Solenoid (CMS) experiment is scheduled for physics data taking in summer 2009 after the commissioning of high energy proton-proton collisions at Large Hadron Collider (LHC). At the core of the CMS all-silicon tracker is the silicon pixel detector, comprising three barrel layers and two pixel disks in the forward and backward regions, accounting for a total of 66 million channels. The pixel detector will provide high-resolution, 3D tracking points, essential for pattern recognition and precise vertexing, while being embedded in a hostile radiation environment. The end disks of the pixel detector, known as the Forward Pixel detector, has been assembled and tested at Fermilab, USA. It has 18 million pixel cells with dimension $100 \times 150\ \mu m^2$. The complete forward pixel detector was shipped to CERN in December 2007, where it underwent extensive system tests for commissioning prior to the installation. The pixel system was put in its final place inside the CMS following the installation and bake out of the LHC beam pipe in July 2008. It has been integrated with other sub-detectors in the readout since September 2008 and participated in the cosmic data taking. This report covers the strategy and results from commissioning of CMS forward pixel detector at CERN.

KEYWORDS: CMS; Pixel detector; Commissioning.

Contents

1. Introduction 2
   1.1 Pixel Sensors and readout chips 3
2. Forward Pixel Components 3
   2.1 Module testing and assembly 4
3. Commissioning of FPIX detector 5
   3.1 Detector operation after installation 7
4. Conclusions and outlook 8

1. Introduction

The Compact Muon Solenoid (CMS) experiment [1] at the Large Hadron Collider (LHC) at CERN is equipped with the largest ever built all-silicon tracking system, enclosed in a superconducting solenoid generating 4T magnetic field. It is designed to provide robust and precise measurement of charged particle trajectories. The innermost tracking device, closest to the interaction region, is the silicon pixel detector which covers a pseudorapidity (η) range $|\eta|\leq 2.5$ matching the acceptance of the central tracker. It contributes high-resolution 3D space points required for the track pattern recognition and the reconstruction of secondary vertices, and thus will play a key role in the physics program of CMS. The pixel detector consists of three cylindrical barrel layers (BPIX) in the central region supplemented by two forward disks (FPIX) at each end (see Fig. 1). The 53 cm long BPIX layers are located at the radii of 4.4 cm, 7.3 cm and 10.2 cm. The FPIX disks extending from ~ 6 to 15 cm in radius from the beam are placed on each side at z=±34.5 cm and z=±46.5 cm. BPix (FPix) contain 48 million (18 million) pixels covering a total area of 0.78 (0.28) m^2. This geometry provides three high-precision hits per track in nearly the full η-range (as can be seen in Fig. 1) which is essential for (a) tagging of heavy quarks and τ leptons, (b) pattern recognition, i.e to confirm or reject track segments proposed by the outer tracking system, and (c) fast tracking and vertexing in the High Level Trigger (HLT) using only the pixel information.

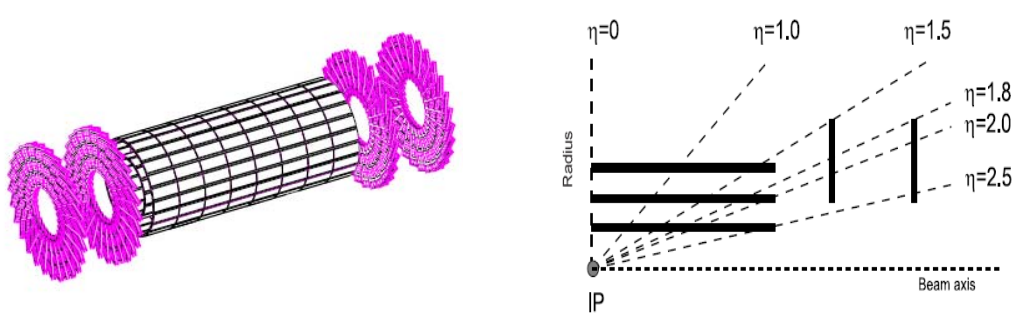

Fig.1: The geometrical layout of the CMS pixel detector and hit coverage for different η regions.

The harsh operating conditions characterized by high track multiplicity and heavy irradiation put severe constraints on the pixel detector design. It necessitates a very fine granularity to resolve nearby tracks and a fast response time to resolve bunch crossings. To achieve this, pixel system with an active area of ~1 m^2 is highly segmented into 66 million pixels. The pixel size of 150 x 100 μm^2 implies a maximum occupancy of 0.033% at full LHC luminosity. The FPIX detectors are deliberately tilted at 20^0 in a turbine-like geometry to induce charge sharing between pixels, since, due to the tilt, drift direction of charge carriers is not parallel to the magnetic field. A position resolution of ≈15 μm in both directions (r-ϕ & z) can be achieved with charge-sharing between neighboring pixels.

1.1 Pixel sensors and readout chip

The hostile radiation environment of the LHC with very high nearly ionizing particle fluxes requires the pixel detector and electronics to be of radiation-tolerant design. The sensors are designed to withstand the expected doses of 3×10^{14} neutron equivalent particles per cm^2 per year of nominal LHC operation. Silicon sensors of the type n+ implants on n-bulk are used along with p-stop isolation technique to provide electrical isolation between neighboring n+ electrodes and multiple guard-rings to ensure a high break-down voltage [2]. This design allows partially depleted operation of highly irradiated sensors after type inversion. Each sensor is 300 μm thick and consists of an array of pixels in two dimensions. The sensor is connected to an array of readout chips (ROCs) through 25 μm Pb-Sn bump-bonds. The pixel ROC, fabricated in 0.25 μm CMOS radiation-tolerant technology [3], is arranged in a 52 × 80 array with a total of 4160 readout channels, organized into double-column readout. Each pixel has an amplifier, shaper, programmable discriminator, storage capacitor and charge injection circuitry for calibration purposes. Each ROC draws ≈120 mW of power during normal operation. The ROC has 32 data buffers and 12 time stamp buffers for low dead time during operation in the CMS trigger. A token bit manager chip (TBM) controls the readout scan (40 MHz) of a group of readout chips. A token scan, initiated by the TBM, performs double-column readout of hit pixels storing charge above the threshold. A common pixel chip threshold is set by a DAC register. Each pixel front end contains a 4-bit DAC trim for individual threshold adjustment. The time information is stored (within 25 ns) in the time-stamp buffer and the address and the analog signal of each hit pixel is transferred to the column data buffer located in the column periphery. Upon receiving a trigger decision, with 3.2 μs latency, the analogue hit information is then piped out through optical links to the readout electronics (Front End Driver modules-FEDs). The analog output is then digitized by a 40 MHz 10-bit ADC. The address of the hit pixel (row and column information) is encoded on six analog levels.

2. FPIX Detector Components

The FPIX disks are populated with 672 detector modules called plaquettes. A plaquette is composed of a silicon sensor bump-bonded ROCs and attached to a flex circuit (a VHDI) laminated on a thin layer of silicon substrate. Each chip reads out 4160 pixels. Due to the geometrical constraint, five types of plaquettes with different dimensions (using ROCs varying from two to ten) are needed. Three or four plaquettes are attached to another flex circuit (an HDI) laminated to a thin wedge-shaped beryllium substrate to form a panel. A total of 192 panels are required. A panel also has a Token Bit Manager (TBM) chip wire-bonded to HDI. A panel is mounted on each of the two sides of a U-shaped aluminum cooling channel and forms a blade; the panel with four plaquettes faces the interaction region while the other with three

plaquettes on the side facing away. The positioning of plaquettes on panels is constrained by the need to cover up the gaps between the plaquettes. There are 24 blades arranged in a fan-like structure to construct a disk. Each disk is split vertically into half-disks so it can be installed with the beam pipe in place. Pairs of half-disks are mounted on a carbon-fiber half service cylinder (HC) containing all the mechanical and electrical infrastructure needed to support, position, cool, power, control and read out the detector.

Figure 2 shows a fully populated half disk and a HC. The FPIX detector consisted of 4 HCs, to be assembled upstream and downstream of the pp LHC interaction point, which were transported to CERN from FNAL in December 2007 where they underwent extensive system tests for commissioning. A pilot FPIX detector, consisting of a HC with two populated blades on each half disk, was also built to pioneer all the assembly and testing procedures. It was also used for several tests to address the integration into the final experimental setup.

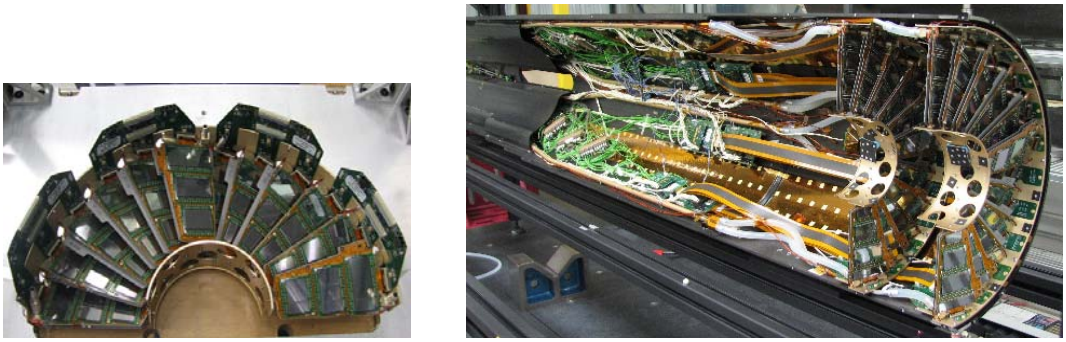

Fig. 2:A half disk (left) with 12 blades and a half Service Cylinder (right) containing two half disks.

2.1 Module testing and detector assembly

After the assembly and quick functionality tests at Purdue University, the plaquettes were shipped to Fermilab where they underwent thorough testing and further assembly. Plaquettes were initially subjected to 2-day burn-in with thermal cycles between +20ºC and -15ºC. Several tests were performed during the burn-in cycling, including verifying an analog output signal from each ROC, checking the functionality of each pixel, etc. Since the pixel detector in CMS will be operated at low temperatures to minimize the effects of radiation damage, plaquettes passing the burn-in underwent detailed characterization testing [4] at -15ºC wherein the quality of plaquettes were evaluated in terms of the characteristics of the sensor, the ROC, the number of bad pixels. These tests included a measurement of the current vs voltage characteristics of the sensor, detection of pixels that are non-responsive, have a non-functional mask bit or a disconnected bump bond. In addition, threshold adjustment, measurements of the gain curve and threshold curve for each pixel have been performed. Only plaquettes that were determined to be of sufficiently high quality were selected for further assembly onto a panel. The assembled panels also underwent testing process similar to that performed on plaquettes. The quality of assembled plaquettes and panels has been very high. Most modules showed less than 0.5% bad pixels per ROC, that were almost exactly corresponding to bad pixels as measured during plaquette testing. The noise characteristics of the modules were also quite impressive. Most modules showed an average pixel noise less than 150 electrons. For comparison, the expected signal from a minimum-ionizing particle is 22,000 electrons, spread over one or two pixels.

3. Commissioning of FPIX detector

The final integration of the FPIX detector into the support structure took place at CERN Tracker Integration Facility (TIF) followed by extensive tests for commissioning prior to the final installation into CMS cavern. The TIF clean room was equipped with all needed services for power, cooling, control, safety and data-acquisition mimicking the final configuration of the experiment as much as possible. This provided the opportunity for the first time to use the detector with the complete DAQ readout chain and realistic services destined eventually for the integration to CMS. The main objectives pursued during the commissioning were thoroughly test and check both the electrical and mechanical aspects of the system and then measure the general performance to ensure that it continued to achieve the required performance obtained during the production phase. The commissioning strategy included, first of all, a sequence of checks (a) all connections: wires, fibers, cooling pipes, temperature and humidity sensors etc., (b) verifying absence of leaks in the cooling circuit, (c) mapping and cleanness of optical fibers, (d) mapping of sensors for detector control system, (e) measuring voltages and currents for low and high voltages. Then, after configuring the detector for readout with proper DAC settings, a sequence of functionality tests were performed. These tests were performed in two steps: (1) quick-tests aimed to get fast feedback on the detector functionality. One of these tests is checking for analog output from each ROC as shown in Fig.3. The other test is to check for no overlapping in the address levels (see Fig.3) that is necessary to correctly decode the pixel addresses. (2) detailed functionality tests [5] focusing on measurement of dead channels, noise, threshold dispersion, gain and pedestal. The detector performance was measured by running cold (-10^{0}C) and warm (+22^{0}C). The commissioning of the BPIX and FPIX detectors were completed in March 2008. The pixel system was inserted into CMS in July 2008 following the installation and bake out of the LHC beam pipe. After the installation, the detector was re-commissioned with the final services.

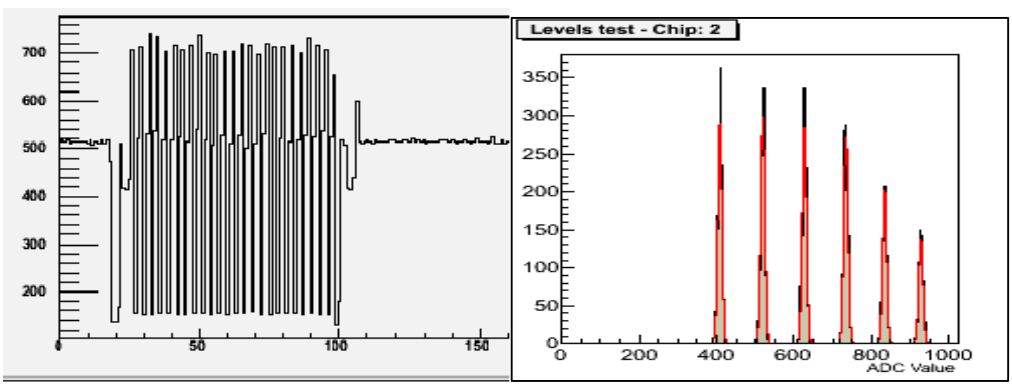

Fig.3: Analog signal from all readout chips in a panel (left). Histogram of six address levels used to encode the row and column information (right).

Pixel Alive test: The functionality of each pixel is checked by verifying that it responds to an injected calibration signal. First, it is tested that masked pixel does not yield signals. Second, the enabled pixel is pulsed several times with calibration signals (with an amount of charge corresponding to ~15000e) and the number of output signals is recorded. The pixel is fully working if all signals are registered; the pixel is defective, if no output signal is registered at all.

Figure 4 shows a ROC with few broken cells. Maps of pixel response are compared with the results from plaquette testing. The test results were very encouraging and the modules were found to attain the high quality matching the FNAL data taken during production. The FPIX detector showed negligible number of dead channels lower than 0.04% per module. A few dead cells were distributed randomly among modules, usually located on the edges and corners of ROCs, with no dead ROCs. Similar results were found for the broken channels after detector installation. Figure 3 shows the fraction of alive pixels per module. The fraction of completely dead cells tops out at ~ .008, equivalent to, at most, one dead double column on a ROC.

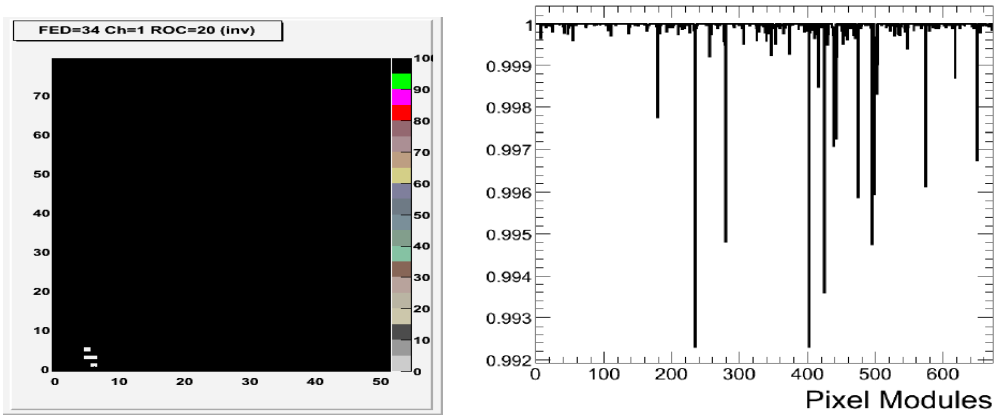

Fig.4: Pixel alive test results for a ROC (left). The fraction of alive pixels / module (right).

S-Curve Test: This test is designed to determine the signal threshold and noise level of each pixel by measuring the so called S-curve, i.e. the efficiency of the pixel as a function of the amplitude of the calibration signal. Each pixel response is obtained by injecting calibration pulses with different Vcal DAC values (1 Vcal = 65e). The S-Curve is fitted with an error function whose turn on and width give threshold and noise, respectively. This test also identifies the noisy pixels which may flood the readout system with a high rate of fake hits and cause significant dead time and data losses. The thresholds of such noisy pixels must be increased or masked completely. Pixels for which the noise is > 260e are classified as noisy pixels and their number were found negligible. Figure 5 shows the preliminary results from the analysis of an S-Curve calibration run during commissioning after installation. It shows the distributions of mean threshold and noise for each ROC on the FPIX modules. Analysis of the results confirmed the

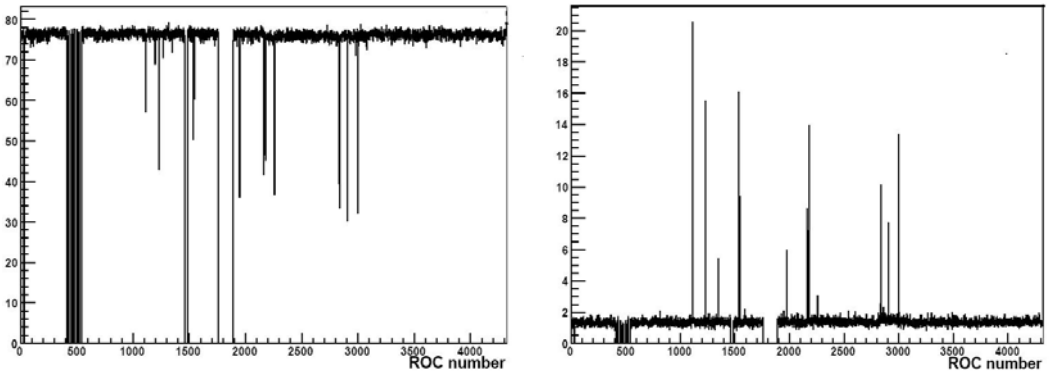

Fig.5: Mean threshold (left) and noise (right) distributions for all ROCs on the FPIX modules. The x-axis represents values in units of Vcal (1 Vcal ~65e).

detector performance as expected from FNAL production. The overall noise is ≈100 electrons, to be compared to a signal of ~22000 electrons.

Gain Calibration: This calibration is designed to determine the gain and pedestal of each pixel. These calibration parameters are needed in off-line analyses such as cluster reconstruction where the measured pulse height in ADC counts has to be converted into the corresponding charge. The calibration is performed by injecting calibration signals with various amplitudes to each pixel and measuring the corresponding pulse heights. Typical gain-curves exhibit the pulse height as a linear function of Vcal over quite a large range. A fit to the linear part of the calibration curve is performed and the gain and the pedestal are recorded from the slope and offset, respectively. Figure 6 shows the preliminary results from the analysis of a gain calibration run during post-installation commissioning. It shows the spectrum of mean gain and pedestal of each ROC on FPIX modules. As can be seen they are fairly uniform for the modules.

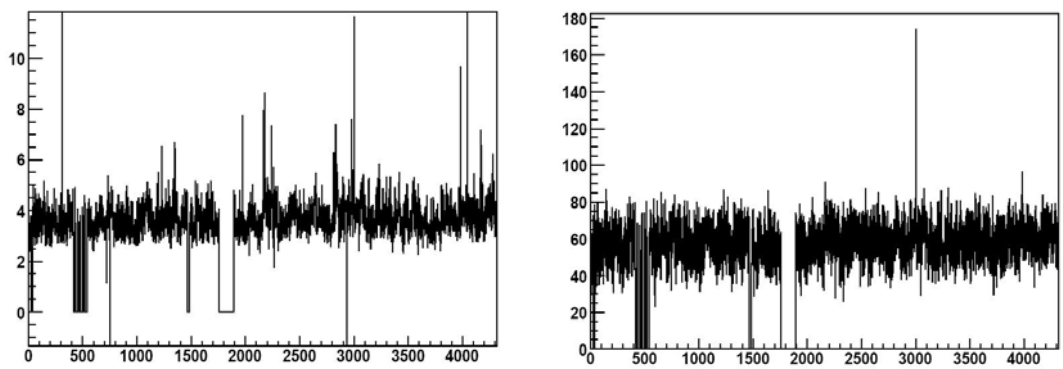

Fig.6: Mean gain (left) and pedestal (right) for all ROCs on the FPIX modules.

Important tests: Several tests were done in order to facilitate the integration and operation of the final FPIX detector. In May 2007, a rehearsal of the final installation procedure of the FPIX detector at CERN was performed. This was successfully followed by an extensive physical and electronic integration test of the subsystem with the rest of the strip tracker. No evidence was found for any performance degradation or interference between pixels and strips. In parallel, a fraction of FPIX detector was tested at Fermilab in a 4 T magnetic field to check the performance. The detector performed as expected and no electronic or mechanical effects were observed due to the strong magnetic field. Prior to the installation of pixel detector into CMS, a small fraction of FPIX called "PIB- Pixel in a Box" consisting of just one panel was installed into CMS in order to gain operational experience. Inclusion of PIB in the readout with other sub-systems during cosmic ray data taking was instrumental in the commissioning of pixel DAQ system and establishing the workflow of data analysis.

3.1 Detector operation after installation

The goal of the FPIX commissioning after installation was to prepare the detector for data taking with CMS. It required accomplishing several projects: (a) checking all connections (e.g. cooling, fibers, power, etc) and their proper mapping (b) getting fully functional detector control system (DCS) which allows operating the detector in a safe mode, (d) establishing the powering up and down procedure, (e) coming up with a suite of calibrations to configure the detector for optimal performance, (f) getting Data Quality Monitoring (DQM) in place to monitor the detector performance, and (g) Integration of FPIX with BPIX and other sub-

detectors in the central DAQ system to make sure that the detector operates without interfering with other sub-detectors. Within a month after the installation in August 2008, pixel detector had a successful first operation with the strip tracker and other sub-detectors in global cosmic runs without magnetic field. About 94% of the FPIX detector was included in the run. The missing section was mainly due to a short in the power distribution developed after installation. More than 35 million events were recorded with cosmic triggers. Preliminary results from the analysis of cosmic data have been quite encouraging. Figure 7 shows the distribution of number of events with digitized hits in the FPIX modules. It also shows the results from a clustering algorithm. It can be seen that most clusters consists of hits from one or two pixels.

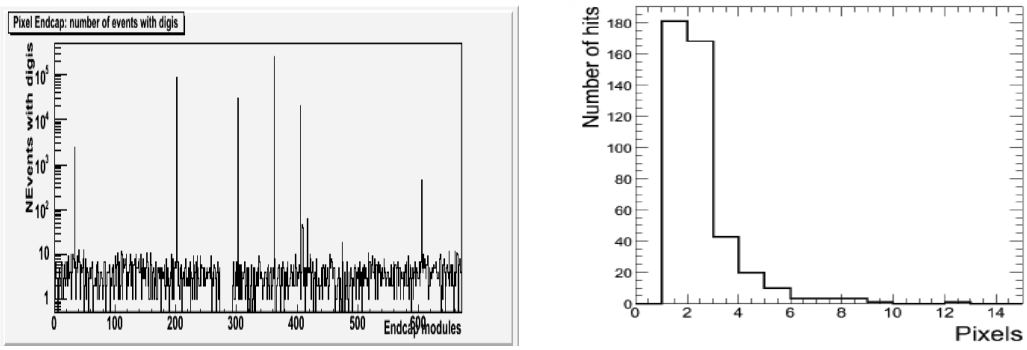

Fig.7 : Distribution of events with digitized hits in FPIX modules (left). Distribution of clusters with different multiplicity of pixel hits (right).

4. Conclusions and outlook

The commissioning of the Forward pixel detector showed that the detector has the same excellent performance it had during production. It has a negligible no of dead channels and an mean noise of less than 150e compared to a MIP signal of ~22000e. The sub detector has been successfully installed into the CMS experiment and commissioned thereafter, within the short amount of time available. The BPIX & FPIX detectors have been fully integrated and were included in global runs with cosmic ray trigger along with other sub-detectors just a month after installation. Detailed detector calibration is underway to attain the most optimal performance. The detector is almost ready for the successful operation in physics data taking after the commissioning of stable beam in the LHC machine expected in summer 2009. We are confident its excellent performance will significantly contribute to the Physics discoveries at LHC.

References

[1] S. Chatrchyan et al., *The CMS detector at the CERN LHC*, 2008 JINST **3** S08004.

[2] G. Bolla et al., *Sensor development for the CMS pixel detector*, NIM A**485** 89 2002.

[3] H. Chr. Kaestli, *Design & performance of CMS pixel detector readout chip*, NIM A**565** 188 2006.

[4] D. Menasce, M. Turqueti, and L. Uplegger, *The Renaissance : a test stand for the Forward CMS Pixel Tracker Assembly*, NIM A**579** 1141 2007.

[5] A. Starodumov et al. Qualification procedures of the CMS barrel pixel modules, NIM A**565** 67 2006.