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The Compact Muon Solenoid Experiment

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The CMS Pixel Detector

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Abstract

The Compact Muon Solenoid Experiment (CMS) will start taking data at the Large Hadron Collider (LHC) in 2007 with the largest silicon tracking detector ever built. As a key component of this tracker, the collaboration is building a silicon pixel detector consisting of two forward/backward disks on each side of the interaction region and three barrel layers. The pixel detector will be crucial to pattern recognition and track reconstruction in the hadronic collisions of CMS and will play a key role in the physics program of the LHC. During the 2007 pilot physics run of the LHC, CMS will run with a subset of the final detector to be installed in 2008. The construction, testing and qualification of the pixel detector is an important aspect of the project and will be described in a separate contribution. In this report, the final design and results from test beam runs and expected performance of the detector are given. The expected radiation tolerance and projected lifetime of the pixel detector will be discussed as well its impact on the physics program of CMS.

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The CMS Pixel Detector

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Abstract

The Compact Muon Solenoid Experiment (CMS) will start taking data at the Large Hadron Collider (LHC) in 2007 with the largest silicon tracking detector ever built. The central components of this tracker consist of two forward/backward pixel disks on each side of the interaction region and three barrel pixel layers. The silicon pixel detector will be crucial to pattern recognition and track reconstruction in the hadronic collisions of CMS and will play a key role in the physics program of the LHC. During the 2007 pilot physics run of the LHC, CMS will run with a subset of the final detector to be installed in 2008. In this report, the final design and results from test beam runs and expected performance of the detector are given. The expected radiation tolerance and projected lifetime of the pixel detector will be discussed as well its impact on the physics program of CMS.

1 Introduction

Collaborators on the Compact Muon Solenoid Experiment (CMS) [1,2] are currently in the final production stages of building a large, multi-layered silicon pixel detector to be installed in the innermost tracking region for the 2008 physics run of the Large Hadron Collider (LHC). The pixel detector will be a crucial component of the track pattern recognition and reconstruction and will play a role in both the offline analysis [4,5] and online high level trigger [6].

The pixel detector will consist of two forward disks on each side of the interaction region of the colliding protons and three barrel layers in the central region. The forward/backward disks are made of twenty-four double-sided blades arranged in a fan like structure with overlapping active areas giving tracking coverage between pseudorapidities of 1.5 to about 2.5. The barrel layers are made with eighteen, thirty and forty-two ladders arranged in a castellated structure. Both the forward/backward and barrel layers have pixel sizes of

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100 × 150 μm for a total of 66 million precision three-dimensional tracking measurements.

The testing of parts during this construction period is the subject of another report in the conference [3]. Results from these tests indicate that the final detector will have 99.9% good channels, with high signal-to-noise ratios of 50-60 and correspondingly high single channel efficiencies.

We report on the final design of the detector, the current production status, results from the test beam runs for the forward and barrel detectors and the expected tracking performance. An effort is also made to estimate the expected radiation tolerance and projected lifetime of detector in the high radiation environment of the LHC. We also discuss the importance of the pixel detector for the online high level trigger, the offline track reconstruction and physics program of CMS.

2 Geometry

The barrel and forward pixel detectors can be seen in Figure 1. The axial and longitudinal locations of the modules for the barrel and forward detectors are listed in Tables 1 and 2. This geometry was optimized to give three pixel hits up to pseudorapidities of about 2.5.

There are three barrel layers centered at the nominal interaction point with a total length of 53.3 cm. Each layer is made up of ladders and each ladder is made up of eight modules (6.63 cm in length) with a small gap of 0.04 cm between each module. The effective gap is somewhat larger since the inactive areas on the sensors is 0.09 cm, giving a total gap between active areas of 0.22 cm. Each full detector module has dimensions of 1.62 cm × 6.63 cm and is connected to sixteen readout chips (ROC's).

The four forward/backward disks consist of twenty-four double sided blades arranged in a fan like structure with a 20° tilt to encourage charge sharing between pixels from charged tracks since now, on average, tracks would impinge on the forward disks with a 20° impact angle. Without this tilt, there would be very little charge sharing since the magnetic field of CMS is parallel to the beam axis. Each blade in a disk has four detector modules called plaquettes on the side facing the interaction region, and three plaquettes on the other side facing away. These plaquettes range in size from two to ten ROC's and are placed so that there is full coverage with the gaps from one side covered by the plaquettes on the other. The active overlapping area is about 2%. The four disks are placed at a longitudinal distance from the origin of ±34.5 cm and ±46.5 cm. There is also space reserved for a future third disk on each side which would be placed at ±58.5 cm.

3 Sensors and Electronics

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. An "n-on-n" design with n^+ implants [7] was chosen. When a charged particle enters the biased sensor, the electrons and holes created by its passage drift in opposite directions; it is the electrons that are collected and amplified by the readout chip to indicate a hit pixel. Electrons have a higher mobility than holes and this design has the benefit that after radiation causes charge sign inversion of the sensor, the highest electric field is still located closest to the collection electrodes. These sensors can still be operated efficiently after charge inversion, but the pixels need to be isolated from each other. To this end, the barrel pixel sensors use "p-spray" isolation and the forward pixel sensors use an open "p-stop" isolation as shown in Figure 2.

There are guard rings at the edge of the sensors which are kept at relative ground and have been designed to operate up to bias voltages of 600 V before breakdown. Test beam runs [8] with unirradiated and irradiated detectors have shown that the barrel sensors still have 99.0% efficiency for tracking charged particles after an exposure of $6 \times 10^{14} n_{\mathrm{eq}}/\mathrm{cm}^2$ and the forward sensors maintained an efficiency of 98.8% after $8 \times 10^{14} n_{\mathrm{eq}}/\mathrm{cm}^2$. This bodes well for running at the LHC since the innermost layer at 4 cm will receive a total dose of about $6 \times 10^{14} n_{\mathrm{eq}}/\mathrm{cm}^2$ after 4-5 years of initial running.

The final version of the production readout chip [9] (called PSI46v2) was designed by engineers and physicists at the Paul Scherrer Institute. It uses a commercial 0.25 μm process and follows standard design rules for radiation tolerance [10]. This chip reads out the $100 \times 150 \mu$m pixels when it is bump bonded to the sensor with either indium (barrel) or lead-tin (forward). The pixels on the PSI46v2 are arranged in a 52×80 array with a double-column readout. The pixels have 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 thirty-two data buffers and twelve time stamp buffers for low dead time during operation in the CMS trigger. Recent test beams to estimate the amount of dead time during high trigger rates have recently been performed [11]. Worst case data losses for layers 3,2 and 1 of the barrel detector are measured to be 0.8%, 1.2% and 3.8% at the full level-1 trigger accept rate of 100 kHz at the design LHC luminosity of 10^{34} cm^{-2} s^{-1}. Data losses at other level-1 trigger rates for the innermost layer are shown in Figure 3 and are dominated by readout losses of the double column due to the waiting time between the trigger and readout token (1.3μs), token passage time (2.1μs) and trigger latency (3.2μs). These data losses are understood by the simulation of the PSI46v2 and are acceptable for data taking up to the design luminosity of the LHC.

4 Expected Performance

The pixel detector will provide three 3D space points up to psuedorapidities of 2.5. It will serve three main purposes for CMS physics:

(1) Provide seeds (in pairs or triplets) for pattern recognition during charged track reconstruction with the all silicon tracker
(2) Improve vertex resolution near the interaction point
(3) Provide fast track and vertex reconstruction using pixel-only information in the online high level trigger. These tracks and vertexes will be used for b, τ and electron identification and the vertexes will be used to locate the primary and multiple beam interactions.

The single hit resolution depends on a number of factors such as the momentum and axial and longitudinal incidence angles on the sensor as well as the presence of nearby hits. The expected average single hit resolution for the barrel and pixel detectors as measured in simulated QCD jets is shown in Figure 4. The average two-pixel cluster resolution is better than 10μm in the 100μm pitch direction and better than 15μm in the 150μm direction. These resolutions are also borne out in recent test beam data [13]. These resolutions meet the specifications laid out in the technical design reports.

5 Current Status

As of the writing of these proceedings, the construction of both the forward and barrel detectors is approximately 50% completed. All the sensors and readout chips are in hand and over half of the barrel modules and forward plaquettes have been built and tested. We are currently on schedule to install the pixel detector into CMS for the 2008 physics run of the LHC. Finally, during the initial 2007 pilot physics/engineering run on the LHC, we will install a small subset of the pixel detector consisting of a single wedge of two layers of the barrel detector and two forward blades. This pilot run detector will facilitate the integration and operation of the final pixel detector for the 2008 physics run.

References

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Figures and Tables

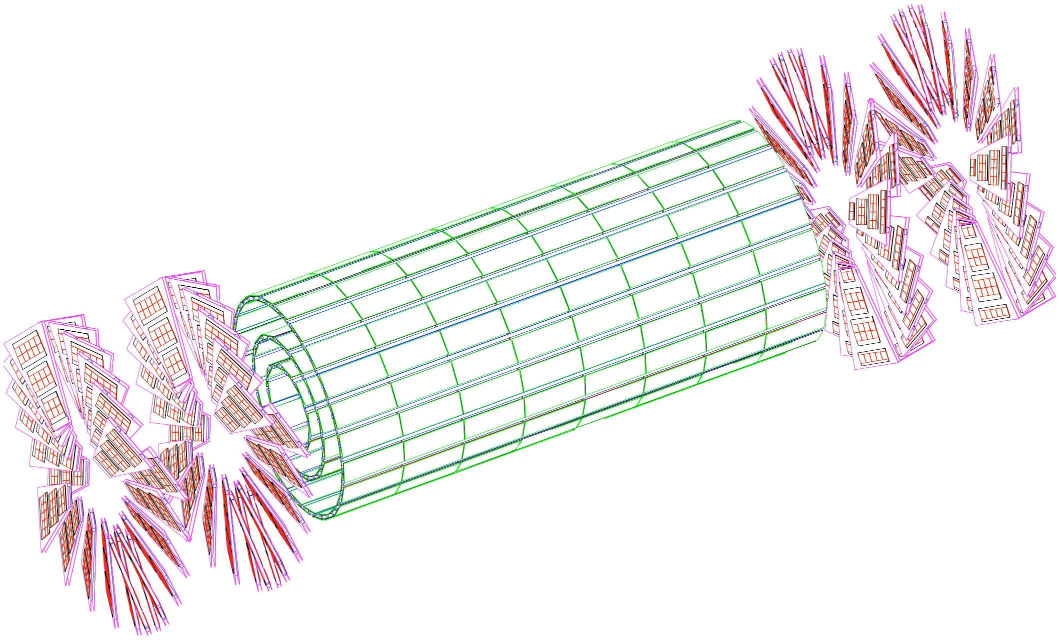

Fig. 1. Geometry of the CMS barrel and forward pixel detectors.

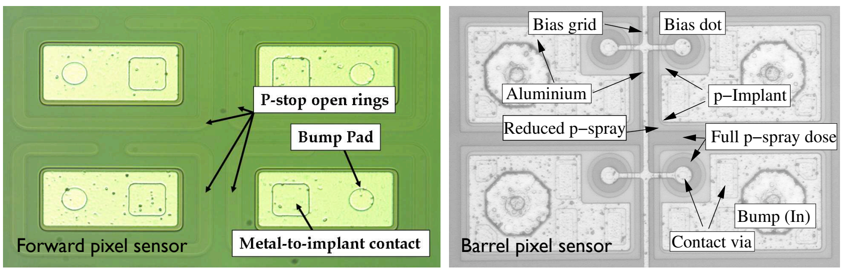

Fig. 2. Layout of the pixels on the sensors for the forward (left) and barrel (right) detectors. The barrel sensors use p-spray isolation and the forward detectors use p-stop isolation.

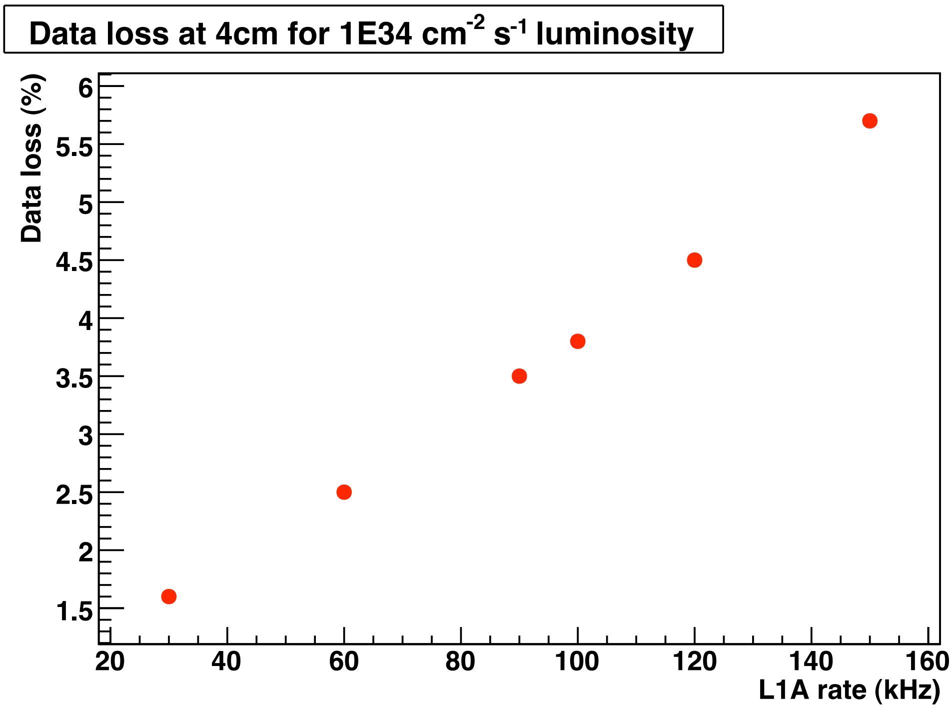

Fig. 3. Data losses as measured from test beam runs of 300 MeV pion beams at PSI [11,12] for the innermost barrel pixel layer. Maximum trigger rates at the design luminosity of the LHC of 10^{34} cm^{-2} s^{-1} will be about 100 kHz.

	Layer 1	Layer 2	Layer 3
Radius (cm)	4.105	7.016	9.888
	4.646	7.555	10.426
Faces in phi	18	30	42
Full/half-modules	128/32	224/32	320/32
Readout Chips	2304	3840	5376
Pixels	9.6M	16.0M	22.4M

Table 1
Final geometry of the CMS barrel pixel detector. At the border of the half cylinders, there are four modules which are half as wide as the rest. Radii are given for the overlapping ladders in the same layer.

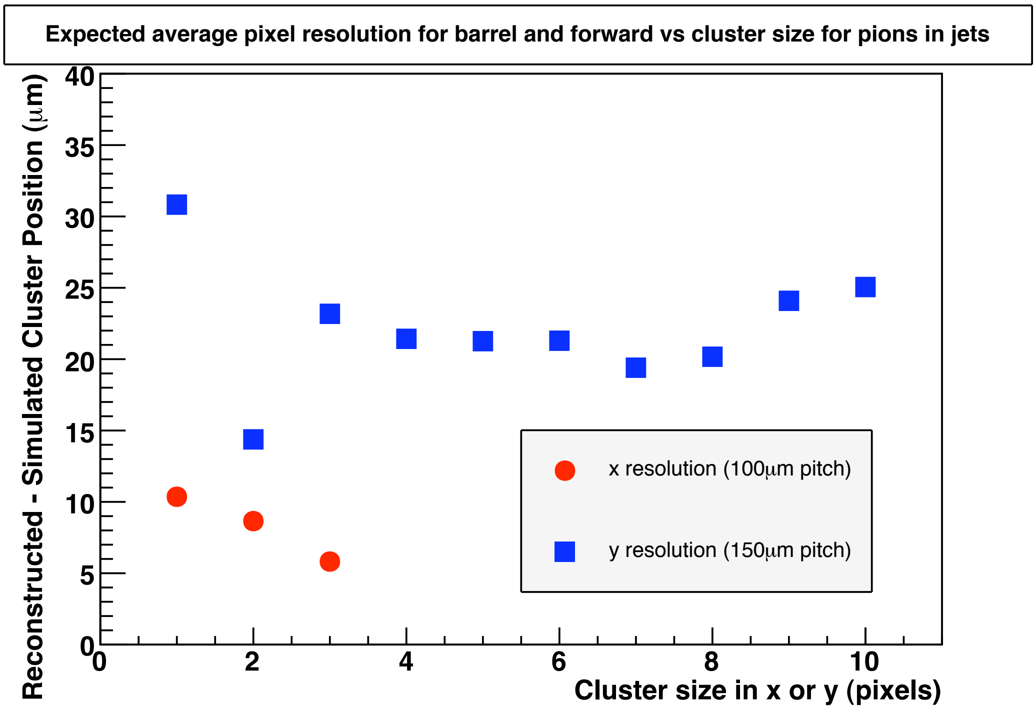

Fig. 4. Expected average single hit resolution of the forward and barrel pixel detectors. These resolutions are those expected in hadronic jets and are averaged over all angles and momenta. The plot includes both the forward and barrel detectors together.

Plaquette	Avg radius (cm)	Facing/Away from IP	ROC's
1	6.50	F	1×2
2	9.04	F	2×3
3	12.0	F	2×4
4	14.7	F	1×5
1	7.81	A	2×3
2	10.7	A	2×4
3	14.7	A	2×5

Table 2
Final geometry of the CMS forward pixel detector.