The Compact Muon Solenoid Experiment

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Operation and Performance of the CMS Silicon Tracker

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Abstract

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OPERATION AND PERFORMANCE OF THE CMS SILICON TRACKER

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The CMS silicon tracker is the largest silicon detector ever built. It consists of a hybrid pixel detector with 66 million channels and a 200 m² silicon strip detector with 9 million readout channels. These proceedings describe the successful operation of this detector during the first four years of the LHC. Results on the operational performance are presented. The resolution and efficiency of the track and vertex reconstruction are measured with data and compared to the results from simulation.

Keywords: CMS; Silicon; Tracker.

1. Introduction

The CMS tracker¹ is an all-silicon semiconductor tracker covering the pseudorapidity range $|\eta| < 2.5$ and operating in a solenoidal magnetic field of 3.8 Tesla. Built for operation in the high luminosity environment of the LHC,² the tracker is designed to have an occupancy below 5% per sensor per bunch crossing¹ and a signal-to-noise (S/N) ratio well above 10.³ It is arranged in a barrel/endcap geometry as shown in Fig. 1, with the barrel layers forming concentric cylinders around the interaction point and the endcap disks enclosing both ends of the barrel. Closest to the beam line is the pixel detector, encompassing 66 million $100 \times 150 \mu\text{m}$ pixel channels. Each pixel sensor has a grid of 52×80 n⁺ pixel cells implanted into the n-type bulk, which forms a junction with the p-type backplane. Surrounding the pixel detector is the strip detector, made of 9.3 million silicon strips. Strip lengths vary from about 7–12 cm and pitches from 80–205 μm , and a single strip sensor can have either 512 or 768 strips. The strips are p⁺ implants on an n-type bulk, with an n⁺ backplane. With a surface area of 200 m², the CMS silicon tracker is the largest silicon tracker ever built.¹

Fig. 1. Quarter longitudinal cross-sectional view of the CMS tracker. The beam line runs horizontally, crossing through the black dot at (0, 0) indicating the nominal position of the interaction point. In this diagram the z coordinate is horizontal and the radial coordinate is vertical. Both coordinates are measured in millimeters. Various values of η are shown with black lines.

2. Operation

The peak instantaneous luminosity delivered by the LHC, reached in late 2012, was $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Approximately half of the events recorded by CMS contained 20–40 overlapping interactions.⁴ The CMS tracker maintained excellent availability and performance in these conditions. 96.3% of the pixel detector and 97.5% of the strip detector was fully operational during the 2009–2013 run period. Figure 2 shows a map of the tracker detector elements color coded by availability.

3. Hit Efficiency and Resolution

The hit-finding efficiency, shown in Fig. 3, exceeds 99% for both the strip and pixel detectors. Using the track trajectory predicted from hits in other layers/disks, the efficiency for a given layer/disk is defined as the fraction of hits found within $500 \mu\text{m}$ of the predicted position on that layer/disk.³ The efficiency for a given strip layer/disk is more loosely defined as the fraction of hits found on the predicted detector module in that layer/disk, where the predicted position is calculated from tracks with at least one hit in the layer/disk subsequent to the one under study.⁵

The pixel hit resolution is measured in layer 2 of the barrel pixel (BPIX) detector from tracks with $p_T > 12 \text{ GeV}$ and hits in BPIX layers 1 and 3. The

Fig. 2. Left: Availability map of the strip detector. The cylindrical TIB and TOB layers are shown “unrolled” with the z coordinate running vertically and the azimuthal ϕ coordinate running horizontally. Red and white modules are masked from the readout. Right: Cluster occupancy map of the pixel detector from run 208686 on December 5, 2012. The cylindrical BPIX layers are shown “unrolled” with the z coordinate running horizontally and the azimuthal ϕ coordinate running vertically. Areas in white represent faulty modules that are not read out.

tracks are refit excluding the hit in layer 2, and the resolution is proportional to the difference between the predicted and actual position of the hit in layer 2. Using this method, the pixel r - ϕ resolution was measured to be $9.4 \mu\text{m}$.³ In the inner barrel (TIB) and outer barrel (TOB) of the strip detector, the position difference between two closely spaced hits from tracks with $p_T > 5$ GeV passing through the overlap regions of two modules in the same layer are used to calculate the hit resolution. By using the difference, the effects of multiple scattering mostly cancel out.⁵ The strip hit resolution varies between 13 and $55 \mu\text{m}$, with a strong dependence on strip pitch. Both pixel and strip measured hit resolutions are consistent with CMS design goals.

4. Radiation Monitoring

The strip and pixel leakage current, which is expected to increase as a function of integrated luminosity due to radiation damage in the silicon bulk,⁶ has been monitored over the course of the LHC run. The results, shown in Fig. 4, indicate that the theoretical models describe the data. As the operating temperature of the tracker is expected to decrease in 2015, the scale of leakage currents induced by radiation damage are expected to decrease accordingly.⁶ Other quantities sensitive to radiation damage, such as the depletion voltage, are also monitored.

5. Track and Vertex Reconstruction

The silicon tracking efficiency has been measured with $Z \rightarrow \mu\mu$ events using a tag and probe technique. The efficiency is defined as the fraction of muons

Fig. 3. Left: Efficiency to find a hit on a strip module vs. layer/disk. The red curve is calculated from a subset of modules that excludes known faulty modules. Right: Efficiency to find a pixel hit within $500 \mu\text{m}$ of its predicted position vs. layer/disk.

Fig. 4. Left: Simulated leakage current vs. measured leakage current in the strips. Right: Leakage current vs. time in the BPIX. The simulation, shown as lines, predicts the shape of the leakage current trend with time, but underestimates the normalization by 40-70%, depending on BPIX layer.

reconstructed in the muon system that also have a matching track in the tracker. A tracking efficiency $>99.5\%$ is maintained in events with up to 20 reconstructed primary vertices.⁷

The primary vertex resolution is estimated from data using the split method,⁵ in which the set of tracks associated to a vertex is divided in half and the difference between the vertex position fit by the two halves is proportional to the resolution. Resolutions for the x (transverse to the beam line) and z (parallel to the beam line) coordinates are shown in Fig. 5. The measured values are consistent with design goals and good enough to distinguish the many overlapping vertices typical of an LHC pp collision.

Fig. 5. Primary vertex resolution as a function of the number of tracks associated to the vertex. The jet enriched data have a minimum jet E_T requirement of 20 GeV, so the tracks in that sample tend to have higher transverse momentum than those of the minimum bias sample. Left: x resolution. Right: z resolution.

6. Conclusion

The CMS silicon tracker has performed to expectations during the 2009-2013 LHC run. More than 96% of the tracker channels were fully operational, and key parameters such as hit efficiency and resolution were measured to be consistent with design goals. As a result of its reliability and excellent sensor performance, the tracker is able to efficiently reconstruct many tracks and interaction vertices per event, contributing critically to the overall physics goals of CMS.

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