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

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Performance of the CMS Silicon Tracker at LHC

Gabriele Benelli for the CMS Collaboration

Abstract

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Performance of the CMS Silicon Tracker at LHC

Gabriele Benelli, *Member, IEEE* on behalf of the CMS collaboration

Abstract—The CMS all-silicon Tracker, comprising 16588 modules covering an area of more than 200m², needs to be precisely calibrated and aligned in order to correctly interpret and reconstruct the events recorded from the detector, ensuring that the performance fully meets the physics research program of the CMS experiment. The performance has been carefully studied since the start of data taking: the noise of the detector, the data integrity, the S/N ratio, the hit resolution and efficiency have been all investigated with time. In 2010 the Tracker has been successfully aligned using tracks from cosmic rays and pp-collisions, following the time dependent movements of its innermost pixel layers. Ultimate local precision is now achieved by the determination of sensor curvatures, challenging the algorithms to determine about 200000 parameters. Remaining alignment uncertainties are dominated by systematic effects that are controlled by adding further information, such as constraints from resonance decays.

I. INTRODUCTION

THE Compact Muon Solenoid (CMS) detector [1] at the Large Hadron Collider (LHC) [2] at CERN is a multi-purpose detector designed to investigate a whole range of high energy physics phenomena. The cornerstone of the ambitious CMS research program is its ability to efficiently detect charged particles produced in the LHC proton-proton collisions and precisely measure their trajectories, vertices and ionization energy loss (dE/dx).

The CMS all-silicon Tracker [3], [4] is composed of an inner Pixel detector and an outer Strip tracker. Fig. 1 shows a schematic view of the CMS tracker and its components.

The Pixel detector is made of a three-layer barrel (BPIX) and two two-disk end caps (FPIX) on each side, with radial coverage from 4.4 cm to 10.2 cm, and pseudorapidity coverage $|\eta| < 2.5$. The 1440 pixel modules provide 66 million readout channels for high precision charged particles trajectory (track) seeding and vertexing.

The Silicon Strip detector (SST) is divided into 4 sub-detectors: the four-layer Tracker Inner Barrel (TIB), the six-layer Tracker Outer Barrel (TOB), the six-disk (three per end cap side) Tracker Inner Disk (TID) and the 18-disk (nine per end cap side) Tracker End Cap (TEC). The radial coverage ranges from 25.5 cm to 1.2 m, with the same pseudorapidity coverage as the Pixel detector ($|\eta| < 2.5$). The CMS SST is the largest silicon detector ever built with an approximate total silicon area of 200 m², made up of 15148 silicon modules, corresponding to 9 million readout channels. The silicon strip modules vary in micro-strip pitch (from 80 μ m to 200 μ m) and in silicon thickness (from 300 μ m to 500 μ m) in order to optimize the detector in terms of occupancy, radiation fluence, total radiation length and tracking precision. A detailed

description of both Pixel and Strip detectors is available [3], [4].

Fig. 1. CMS Tracker schematic exploded view showing Pixel and Strip sub-detectors.

In the following, we will describe the detector status and its operation, giving an overview of tracking and vertexing performance. The integration of tracker online conditions in the CMS event reconstruction will be described and the recent progress in the tracker alignment will be presented.

II. DETECTOR STATUS AND OPERATIONS

In the first two years of LHC collisions the CMS Tracker achieved more than 98.5% uptime, counting as downtime also the periods when High Voltage (HV) was turned off due to LHC beam conditions. This performance depends strictly on the successful daily operation of its complex infrastructure.

A. Cooling

Both Pixel and Strip detectors are liquid cooled in order to absorb the large amount of power dissipated by the on-detector readout electronics (>60 kW), minimize radiation damage from the high hadron fluences and keep the operating temperature stable. Three separate cooling plants circulate the C₆F₁₄ cooling liquid (chosen for its high volatility and low temperature viscosity) at +4°C for SST and at +7.4°C for the Pixel detector. One of the two SST cooling plants suffered from a few leaks, which resulted in the closing of five of the 180 cooling lines. The cooling situation is now stable and preparations are being made in order to operate both detectors at significantly lower temperatures and cope with the expected increase in sensor irradiation at the nominal LHC design luminosity expected after the next long LHC shutdown.

B. Power Supply System

The CMS tracker is powered by a custom power supply system [5], made of 96 Pixel power supplies and 1944 Strip ones. The supplies are housed on the balconies of the experimental cavern. They are connected to the detector

modules via cables of 30-50m length and they are controlled by CAEN mainframes in the accessible service cavern. After an initial 1% level of power supply failure rate in 2010, the number of failures has decreased to less than one (out of more than 2000) power supply replacement needed per month. The ramp-up time for the CMS Tracker is dominated by the large number of Strip power supplies and it has been significantly reduced to approximately 70 seconds, a negligible effect on the global CMS data-taking efficiency.

C. Detector Control System

The CMS Tracker has an integrated Detector Control System (DCS) [6] to control and monitor both Pixel and Strip detectors. The system has performed very reliably and in the last year several new features have been added to optimize regular data-taking but also to facilitate calibration and special detector performance operations. In particular, developments allowed the collection and analysis of leakage current, temperature and low voltage data collected by the Detector Control Unit (DCU) ASICs from the individual modules, a key ingredient in monitoring radiation damage effects.

D. Data Acquisition

The data acquisition (DAQ) of the CMS Tracker represents approximately 70% of the total CMS DAQ and it performed very stably. The main sources of downtime have been hardware failures of Front End Driver (FED) electronics and VME crate hardware. The firmware was updated for both detectors to increase robustness and cope with higher multiplicity events typical of the 2011 LHC collisions. Optimized tracker configuration procedures have reduced dead-time at the start and stop of data-taking runs.

E. Data Quality Monitoring

The CMS Tracker Data Quality Monitoring (DQM) [7] is an essential tool for early detection of hardware and data-taking problems. Several potential tracker failure scenarios, ranging from power supply to DAQ issues, have been identified and DQM tools are ready to spot any potential problem in real time. A feedback loop with CMS analysis groups insured robustness of data analyses against these potential failure modes.

F. Detector operations

The number of inefficient strip modules is about 2%. This number includes some permanently damaged modules, while about 1% is expected to be recovered during the next long LHC shutdown (mostly due to low/high voltage shorts inside the detector). About 3% of Pixel modules are currently inefficient: mostly due to a single point loss in service electronics in one of the end caps, and to problems consistent with failing wire bonds in a few barrel modules. The CMS tracker design is characterized by high redundancy, so that a much higher number of inefficient modules is tolerated without affecting tracking performance. Fig. 2 shows a Strip Tracker map of inefficient modules. This map is produced as part of the regular offline calibration workflow.

Fig. 2. Strip Tracker map of inefficient modules. The modules in white are inefficient modules. The modules in blue are efficient. The map represents an exploded view of the Strip Tracker. It is automatically produced as part of the offline calibration workflow, pointing out both modules that were not included in the data-taking and the ones that, failing the calibration, will be masked in the event reconstruction.

Online software performed reliably, allowing the necessary calibrations, executed regularly as integral part of the detector commissioning. These calibrations cover a range of key settings, for example for the Strip detector they are: internal synchronization, ADC gain calibrations, baseline adjustment, pulse shape tuning, ADC noise and pedestal values and latency scan. Most of these settings need adjustment only when a re-commissioning of the detector is necessary, after a change in the hardware for example, but some of them, such as noise and pedestal values, are calibrated often to ensure the best data quality. Regular HV (bias) scans are performed to monitor the depletion voltage. This is particularly important with the expected increasing radiation damage. For the moment, no change in the depletion voltage has been observed [8].

Leakage currents are closely monitored on both detectors. The currents are increasing, showing the effects of radiation on silicon, and they are compatibles with expectations. Lower operating temperatures are foreseen to mitigate radiation damage in the future.

III. TRACKING AND VERTEXING PERFORMANCE

Clusters signal to noise ratios are constantly monitored for each strip module. The most probable values of the corresponding Landau distributions are approximately 20 across the whole Strip detector, guaranteeing optimal operation. Single hit efficiencies for active Strip modules are larger than 99.9%.

Hit resolution ranges from $9\mu\text{m}$ to $35\mu\text{m}$ in the Pixel detector, while in the Strip one it varies from $15\mu\text{m}$ to $45\mu\text{m}$.

Primary vertex reconstruction uses an adaptive vertex fit on tracks within 1 cm of each other along the beam direction (z in the CMS coordinate system). The resolution for primary vertices with more than 30 tracks is about $25\mu\text{m}$. The primary vertex reconstruction efficiency, shown in Fig. 3, is very close to 100% for vertices with more than 4 tracks.

Fig. 3. Primary vertex reconstruction efficiency as a function of the number of tracks associated to the vertex, for data (black dots) and Monte Carlo simulated events (red dots).

With the increase in LHC instantaneous luminosity, event pile-up and backgrounds are becoming very significant. Fig. 4 shows the comparison of the number of primary vertices between low and high luminosity LHC collision runs: the average number of vertices per event increased from about five to almost eight vertices.

Fig. 4. Number of reconstructed primary vertices for a low luminosity (black histogram) and a high luminosity (red histogram) LHC collision run.

The track and vertex reconstruction are handling the harsher conditions without showing efficiency degradation. One of the many tests designed to validate the track reconstruction robustness against event pile-up is shown in Fig. 5: the tracking efficiency of simulated muon tracks embedded in collision data minimum bias events. This type of test shows over 99% efficiency for muons and pions.

Fig. 5. Selection efficiency as a function of track momentum, for simulated muon tracks (solid dots) and for simulated muon tracks embedded in LHC collision data minimum bias events (hollow dots).

IV. ONLINE TO OFFLINE (O2O) CONDITIONS TRANSFER

In order to assure the most accurate reconstruction and to provide the correct configuration to the high level trigger (HLT), a set of tracker online conditions are transferred (O2O) to the offline conditions database (DB). Some of these transfers are needed only in case of major changes in the tracker configuration; other calibration quantities are transferred continuously.

An example of a timestamp based O2O is the DCS Voltage Status O2O. The information from the 8000 CAEN power supply channels (two low voltage and two high voltage channels per power supply) is transformed into a compressed condition object, which describes the voltage status of all Strip tracker modules. The condition information is organized in Intervals Of Validity (IOVs), which in this case are timestamp based (a new IOV is created at each change in any of the power supplies). Event reconstruction properly handles modules that did not have voltage on, discarding their hits and improving tracking performance.

Another example of O2O is the one needed when the Strip tracker readout configuration is switched between peak and deconvolution modes. In peak mode, the whole strip signal shape is sampled, resulting in lower noise, while in deconvolution mode the signal shape is obtained from three consecutive samples, effectively reducing the whole signal shape to 25 ns and allowing to disambiguate hits in high occupancy, high event pile-up scenarios, up to the nominal 40MHz LHC collision frequency. The peak readout mode is the preferred one to cosmic data taking, while the deconvolution is the collision data default readout mode. This O2O is time critical, since its conditions are necessary to configure the HLT before a new data-taking run can start. A fast switching O2O procedure was implemented to speed up transfers that are simply toggling between two states already present in the offline DB. This development enables cosmic data collection during the short LHC inter-fill times for alignment purposes, increasing the overall data-taking efficiency of the detector.

V. ALIGNMENT

A critical requirement for high quality tracking is to know the alignment of the tracking modules with high precision. Several causes affect the position of tracker components with time, such as mechanical and thermal stress due to the large magnetic field and temperature variations.

Several methods are used to align the CMS tracker:

- optical survey,
- laser alignment and
- track based alignment.

While the three methods are complementary, the track based one allows to reach the highest precision. It consists in the minimization of a system of $O(100k)$ equations, where the variables are the track residuals for the 6 degrees of freedom of each module. With track residual, we refer to the difference between the predicted track hits and the actual observed hits in the modules. Two complementary algorithms have been developed to separately do a global and a local minimization.

Fig. 6. Illustration of the module local coordinates u , v , w and the corresponding rotations α , β , γ for a single-sided strip module. The corresponding u' , v' , w' coordinates are defined to be parallel to u , v and w and always pointing in the positive ϕ , z or r direction, so that v' is always directed along the strips, while u' corresponds to the global r - ϕ coordinate.

Before the first LHC collisions, the CMS tracker was aligned using three million cosmic ray charged particles [9], and this sample statistics was sufficient to reduce the remaining uncertainty to systematic effects. Table 1 shows the uncertainty on the track residuals in the modules local u and v coordinates, which are illustrated in Fig. 6.

TABLE I. RMS OF THE DISTRIBUTION OF THE MEDIAN OF THE TRACK RESIDUALS IN THE U' AND V' LOCAL COORDINATES (LOCAL X AND Y) OF MODULES WITH MORE THAN 30 HITS IN COSMIC RAY DATA

	before [μm]	global [μm]	local [μm]	combined [μm]	combined MC [μm]	ideal MC [μm]	modules >30 hits
BPIX (u')	328.7	7.5	3.0	2.6	2.1	2.1	757/768
BPIX (v')	274.1	6.9	13.4	4.0	2.5	2.4	
FPIX (u')	389.0	23.5	26.5	13.1	12.0	9.4	393/672
FPIX (v')	385.8	20.0	23.9	13.9	11.6	9.3	
TIB (u')	712.2	4.9	7.1	2.5	1.2	1.1	2623/2724
TOB (u')	168.6	5.7	3.5	2.6	1.4	1.1	5129/5208
TID (u')	295.0	7.0	6.9	3.3	2.4	1.6	807/816
TEC (u')	216.9	25.0	10.4	7.4	4.6	2.5	6318/6400

With the use of collision data, the alignment of Pixel end-caps modules improved significantly, while new methods could be implemented to address the so-called “weak” modes. Weak modes are movements in the Tracker to which the alignment algorithms are not very sensitive (multiple minima

are found in the minimization process). These weak modes could lead to alignments that result in a systematic bias of physics quantities. Using Z^0 boson di-muon decays it is possible to introduce a mass constraint that helps address weak modes, such as twisting. Fig. 7 shows the reconstructed Z^0 mass as a function of the pseudorapidity η of the positive muon. The plot clearly shows a systematic bias introduced by a weak mode, which virtually disappears when the mass constraint is applied in the alignment.

Fig. 7. Z^0 reconstructed mass (from di-muon decay) as a function of pseudorapidity η of the positive muon in 2011 collision data. In red the result without using the Z^0 boson mass constraint, in blue the result with the mass constraint and in black the MC ideal case.

In order to improve alignment even further a new set of degrees of freedom has been added to take into account the sensor deviation from ideal planarity. Fig. 8 shows that the assumption of ideally flat sensors is not a good description of reality, so taking into account the sensor curvature improves alignment significantly.

Fig. 8. Observed track residuals in the innermost TIB layer modules local z coordinate versus the relative hit position in local x coordinate, with (blue squares) and without (green dots) sensor curvature parametrization, in cosmic ray data.

The increased precision of the alignment is reflected in a better tracking performance.

VI. CONCLUSIONS

The CMS all-silicon tracker is performing excellently, allowing the CMS collaboration to pursue its physics goals while coping with the increasing challenges related to the sharp increase in luminosity and consequent radiation damage.

The detector is in very good shape and will be further improved during the long LHC shutdown, scheduled for 2013.

Radiation damage started to be visible in silicon, but it does not yet affect the tracking and vertexing performance. The operation temperatures of Pixel and Strip detectors will be lowered in order to reduce the radiation damage effects of the expected increasing hadron fluence. Several procedures have been optimized to maximize uptime and to allow a more accurate reconstruction using also online quantities.

The alignment of the CMS tracker has reached a precision and a level of automation that allows the possibility to follow relative detector components movements and to provide this information in time for the CMS event reconstruction.

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