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Calibration and Monitoring of the CMS Silicon Strip Tracker detector

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The CMS Silicon Strip Tracker (SST) is the largest detector of this kind ever built for a high energy physics experiment. It consists of more than ten millions of analog read-out channels, split between 15,148 detector modules. To ensure that the SST performance fully meets the physics requirements of the CMS experiment, the detector is precisely calibrated and constantly monitored to identify, at a very early stage, any possible problem both in the data acquisition and in the reconstruction chain. Due to its high granularity, the operation of the CMS SST is a challenging task. In this paper we describe the reconstruction strategies, the calibration procedures and the data quality monitoring system that the CMS Collaboration has devised to accurately operate the SST detector.

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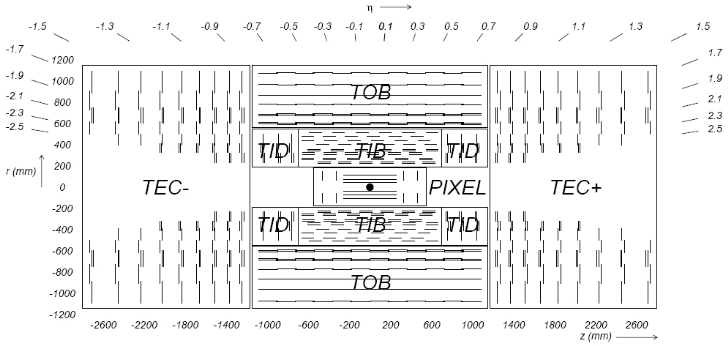

Figure 1: Schematic cross section of the CMS Tracker detector. Each line represents a detector module. Double lines indicate back-to-back modules which deliver 2D hits. The different detector subsystems are shown: Pixel, Tracker Inner Barrel and Disks (TIB/TID), Tracker Outer Barrel (TOB) and the two Tracker End Caps (TEC) .

1. Introduction

The research program of the CMS experiment [1] requires a robust, efficient and precise reconstruction of the charged-particle trajectories as well as of primary and secondary vertices. These attributes should be maintained during the 10 years of the expected lifetime of the CMS experiment in the harsh radiation environment of the LHC collider. In order to fulfill these constraints a tracking device entirely based on silicon detectors has been realized, having high granularity, read-out speed and radiation hardness.

The CMS Tracker [2] surrounds the interaction point, it has a length of 5.8 m and a diameter of 2.5 m, with an overall pseudo-rapidity acceptance of $|\eta| < 2.5$ (Fig. 1). It is composed of a pixel detector with three barrel layers at radii between 4.4 cm and 10.2 cm and a Silicon Strip Tracker (SST) detector with 10 barrel layers extending outwards to a radius of 1.1 m. The system is completed by end caps which consist of 2 disks in the pixel detector and 3 plus 9 disks in the SST on each side of the barrel. This layout ensures at least 9 hits in the SST in the full range of $|\eta| < 2.3$ with at least 4 of them being two-dimensional measurements.

The SST is composed of 15,148 detector modules. Each module carries either one thin (320 μm) or two thick (500 μm) single-sided silicon strip sensors for a total of 24,244 sensors, making up a total active area of 198 m^2. Strip shaped diodes are formed by p+ implantation into an n-type bulk. Sensors are segmented in either 512 or 768 strips, reflecting the read-out modularity of 256 channels (two 128-channel front-end chips, the radiation-hard APV25 [3], multiplexed to one read-out channel). The strip pitch ranges from 80 μm in the inner layers to 180 μm in the outer layers, providing a single point resolution from 23 μm to 53 μm. The signals of each microstrip are amplified, shaped, sampled and temporary stored by the APV25. Upon a positive first level trigger decision the analogue signals of all channels are multiplexed, converted in optical signal and transmitted via optical fibers to Front End Driver (FED) boards in the service cavern where the analogue to digital conversion takes place. This analogue read-out scheme was chosen to ensure: (i) optimal spatial resolution from charge sharing; (ii) operational robustness and ease of monitoring due to the availability of the full analogue signal; (iii) robustness against possible electronic common mode noise; (iv) less radiation hard electronics and reduced material budget as the analogue to digital conversion and its power needs are shifted out of the tracker volume.

The subsequent copious amount of SST data to handle and control implies a robust and reliable set of calibration and monitoring procedures to achieve the expected detector performance. These procedures will be described in the following sections together with an overview of the SST local reconstruction chain.

2. The SST local reconstruction chain

The data processed by the FED devices are sent to the offline computing farms where further reduction and filtering take place, resulting in a clean sample of tracks. The data reduction proceeds in two phases, identified as local and global reconstruction respectively. In the first phase, local hits on the silicon sensors are reconstructed from the strip signal. In the second phase, tracks are constructed fitting the hits collected by the pattern recognition algorithms that navigate through the tracker layers. Further details on the track reconstruction are discussed in Ref. [4]

The local reconstruction in turn is performed in two stages: cluster reconstruction and hit conversion.

2.1 Cluster reconstruction

The FED data contain the basic hit information: the strip position number and the strip pulse height (signal) in ADC counts. The signal is generally pedestal-subtracted and Zero-Suppressed, unless specific samples of raw data are needed for monitoring and calibration purposes.

The cluster reconstruction algorithm allows to further suppressing the strip noise fluctuations and to identify the groups of adjacent strips (cluster) associated to the passage of a charged particle through the sensor. The identification is based on a set of three thresholds ($\mathrm{T_S}, \mathrm{T_N}, \mathrm{T_C}$) to be exceeded by the signal-to-noise ratio (S/N) of the cluster strips. The noise level of each strip is evaluated during the periodic commissioning of the detector. Clusters are reconstructed by searching for a seed strip with a signal-to-noise ratio (S/N) greater than T_S. Neighboring strips are attached to the cluster if their signal-to-noise ratio exceeds T_N. The total signal size of the cluster must exceed the threshold T_C times the quadratic sum of the individual strip noise. The signal of a cluster is the sum of the ADC counts of all associated strips. Standard values adopted for the set of thresholds ($\mathrm{T_S}, \mathrm{T_N}, \mathrm{T_C}$) are (3, 2, 5). Under the assumption of gaussian noise fluctuations this set of thresholds guarantees a rejection power of three orders of magnitude. Further optimization of the thresholds should allow rejecting the non gaussian components of the strip noise, if needed.

To guarantee a uniform response function along the tracker and correct for the variations in the read-out amplification, a gain correction is applied to the ADC counts of each strip. Furthermore, the clustering algorithm accesses the information of the strip quality and rejects from the cluster the strips flagged as faulty.

2.2 Hit conversion

The hit conversion associates to every cluster a global position and corresponding errors to be used for the track reconstruction. The hit position is determined from the centroid of the signal heights of the cluster strips. The position is corrected for the estimated Lorentz shift that the charge carriers experience during their drift in the silicon sensors due to the 4 T solenoidal magnetic field of the CMS detector. The uncertainty on the module positions due to the misalignment is taken into account by quadratically adding an Alignment Position Error to the hit errors.

3. The SST Calibration procedures

The SST local reconstruction requires a variety of condition data in order to interpret and reconstruct the events recorded from the detector. These condition data include the cabling map, used to group the FED data according to detector modules, as well as the following calibration constants: (i) the pedestal and noise level of each individual strip; (ii) the map of faulty components; (iii) the signal gain correction; (iv) the Lorentz angle values for each module.

The condition data are held in two central Oracle databases accessed by the online HLT system as well as by the offline reconstruction and analysis applications. These databases are referred to as Condition databases. Each set of condition data is associated to an interval of validity (IOV) defined as the range of consecutive events to which these conditions are applied. Calibration constants for a given IOV may be derived from a set of promptly analyzed events belonging to the same IOV or from commissioning events gathered just before the acquisition of physics runs.

During the detector commissioning stage sets of calibration data are collected to discover the active components of the SST, to tune the parameters of the read-out chain and to measure the level of pedestal and noise of each detector channel. The commissioning data are written in a specific Oracle database designed to efficiently configure the read-out devices and decoupled from the Condition databases. Therefore dedicated applications are needed to transfer to the Condition databases the calibration data needed by the reconstruction. To guarantee that same conditions are used in the device configuration, in the HLT and in the offline reconstruction, the transfer is automatically performed whenever a new configuration of parameters is uploaded in the read-out devices for the data acquisition of physics runs.

Beside the simple transfer, the condition data are subjected to a format manipulation to provide the best suitable structure for the reconstruction. Actually, the processing speed and the memory footprints are critical aspects of the reconstruction applications. The highly granular information available in the SST condition data can significantly contribute to the run-time performance of the process. In order to speed up the data loading from the databases and to reduce the memory allocation, the calibrations constants are structured in packed format and transferred as Binary Large Objects (BLOB). For instance, this strategy reduces the size of the strip noise data from the 40 MB that would have been necessary with an uncompressed format to 11 MB, preserving the same measurement precision. The calibration constants evaluated in the SST commissioning phase and systematically transferred in the configuration databases are the strip pedestal and noise values, the set of disabled components, the thresholds of the Zero-Suppression. In the following we will focus on the calibration quantities evaluated from particle data with offline analyses. For a detailed description of the commissioning procedure see Ref. [5].

3.1 Faulty Components Identification

Faulty components in the CMS SST detector can negatively affect the tracker reconstruction performance. Isolated noisy channels, badly configured electronic system, dead components, temporary failures of some services (like power supply trips) are common causes of efficiency losses and fake rate increase. To recover this possible deficit, both the clustering and tracking algorithms exploit the information of the detector quality. The identification of problems relies on several algorithms, each designed to recognize a specific source of failure. Each algorithm provides a list of bad components. Multiple lists can coexist in the Condition databases and are combined in a single one when used in the reconstruction. In this approach a leading role is covered by the data quality monitoring system that allows to quickly spotting unforeseen behaviors from data.

The first phase in which faulty components are identified is the commissioning stage. In that task the list of inactive or not properly working components is identified and transmitted to the Condition databases. The finest granularity generally achieved is at the level of a read-out chip (128 consecutive detection channels).

Isolated noisy channels are identified in the offline analyses looking at the cluster occupancy in each region of the sensors. Given that the average flux of particles through a sensor is uniform, an high occupancy, respect to the mean, measured in a part of the sensor is an indication of specific noisy channels. The usual cause of these ‘hot’ channels is an underestimation of the noise fluctuation, with the consequent effect that the powerfulness of the clustering algorithms in suppressing the fake signals is reduced. A first solution adopted for these channels is to increase the thresholds used by the clustering algorithm in order to further suppress the noise without rejecting the signal produced by a particle, thanks to the high signal-to-noise ratio that characterizes the SST (above 28). This approach reduces the fake rate, keeping the channels still active. Inefficiencies in the procedure could occur after some years of operation, when the irradiation damage will reduce the signal-to-noise ratio of the detector. In some cases a definitive masking of few channels not cured by the increase of thresholds is needed. The list of these channels is written in the Condition databases and made available in the reconstruction.

Another kind of failure is related to inefficient or dead channels. In that case a reduced occupancy is found with respect to the average occupancy of a module. The identification of these components is connected to the measurement of the hit reconstruction efficiency and requires enough amount of data. The adopted procedure exploits the capability of the Kalman fitter to provide optimal predictions of the track parameters on the surfaces crossed by a track, including the expected impact point. The efficiency measurement consists in checking the presence of a reconstructed hit compatible with the expected position on the sensor. The analysis is performed for all modules of a layer at a time. In order to avoid any bias due to correlations between hit and track finding efficiencies none of the hits in the layer under consideration is used in the track reconstruction.

The bad strip occupancy and the hit reconstruction efficiency of the SST modules have been already evaluated in a number of tests with cosmic muon events. The measured mean number of noisy channels is of the order of 10^{-3} and the measured efficiency is of 99.8%.

3.2 Signal response calibration

The calibration of the detector response function along the full SST is an essential component for both the detector monitoring and the exploitation of particle identification techniques. These techniques, based on the measurement of the energy loss in the SST sensors, rely on the uniformity of the response to the signal generated by the passage of charged particles through the detector. Defects in the sensors, instability in the amplification stages of the read-out devices, imperfect synchronization of the SST system can affect the homogeneity of the response function. An important contribution to the amplification non-uniformities comes from the front-end laser drivers that converts the strip electric signal in optical signal, for transmission in the service cavern without significant signal-to-noise reduction. Although the electrical-to-optical conversion is linear, the gain factor applied depends on several configuration parameters and is sensible to the temperature of the laser drivers. For this reason the calibration of the optical gains is included in the regular commissioning procedures of the SST. Even if the optimal settings are applied to the laser drivers, the residual non-uniformity is still at the level of 10%, without taking into account other additional non-uniformities in the silicon sensors and in the read-out chain upstream the laser drivers.

The ultimate equalization of the charge response is obtained by looking directly at signals produced by particles. The charge released in thin material layers is Landau distributed, with Most Probable Value (MPV) proportional to the distance traveled by the particle through the active material of the detector[1]. The procedure developed evaluates the inter-calibration constant of each module (or its fraction) as the factor that equalizes to a given reference value the MPV of the signal distribution for the clusters collected on the same module (or its fraction). The signal of each cluster is before normalized to the distance travelled through the active material of the module, using the information of the track incidence angle on the detector and the thickness of the sensor. The MPV is obtained fitting the distributions with a Landau curve.

Detailed studies on the performances of this method have been done with Monte Carlo Minimum Bias events, simulating the scenario of first data taking (Fig. 2). The resolution of the approach depends mainly on the amount of data collected in each distribution. In the startup scenario, after few days of data acquisition, the resolution achieved is of the order of 10^{-2}. Systematic effects have also to be controlled, like the different momentum spectra that illuminate the modules located in distinct pseudorapidity and radial areas of the SST as well as the saturation effects in the electronic channels due to extremely inclined tracks.

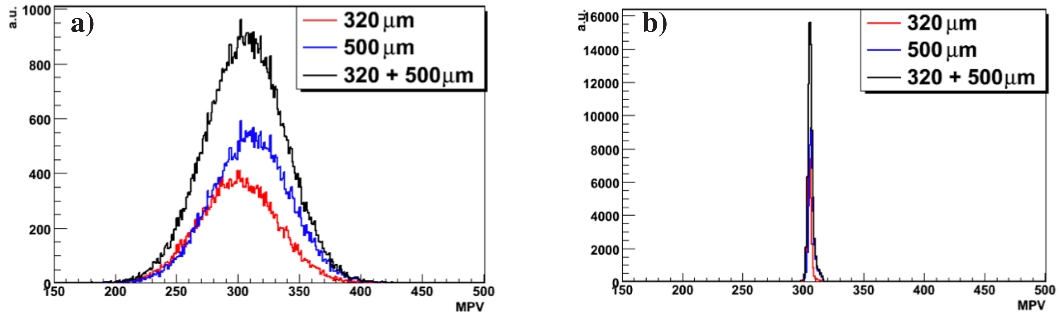

Figure 2: Distribution of the MPV of signal distributions for the clusters reconstructed in all read-out chips of the SST, after collection of 20 millions of simulated Minimum Bias events, before (a) and after (b) the charge response calibration.

3.3 Lorentz angle calibration

Due to the intense magnetic field in the CMS Tracker volume, the drift motion of the charge

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[1] Indeed the most probable energy loss in thin detectors normalized to the detector thickness, x, scales as $a\ \ln x + b$. This residual non-linearity is measured from data and easily taken into account [6].

carriers affected by the Lorentz force can generate a shift of the cluster position by 15-25 μm depending on the detector thickness. For the SST only the drift of the holes is important, since the holes are the charge carriers collected on the p+ segmented side of the sensor. The hole deflection respect to the drift direction, defined as Lorentz angle θ_L , is given by $\tan\theta_{\mathrm{L}} = \mu_{\mathrm{H}}\mathrm{B}$ where the Hall mobility μ_{H} is the drift mobility in a magnetic field. The Hall mobility depends on several parameters constantly monitored during the SST operation, as the bias voltage, the sensor depletion voltage, the sensor temperature. Changes in these parameters can modify the drift properties and finally affect the hit resolution. On top of that, the high irradiation doses absorbed by the silicon sensors in the LHC environment will gradually change their drift properties and consequently also the position resolution. For these reasons a direct measurement of the Lorentz Angle from data is periodically foreseen, as calibration procedure and monitoring tool of the variations of the conditions in the sensors.

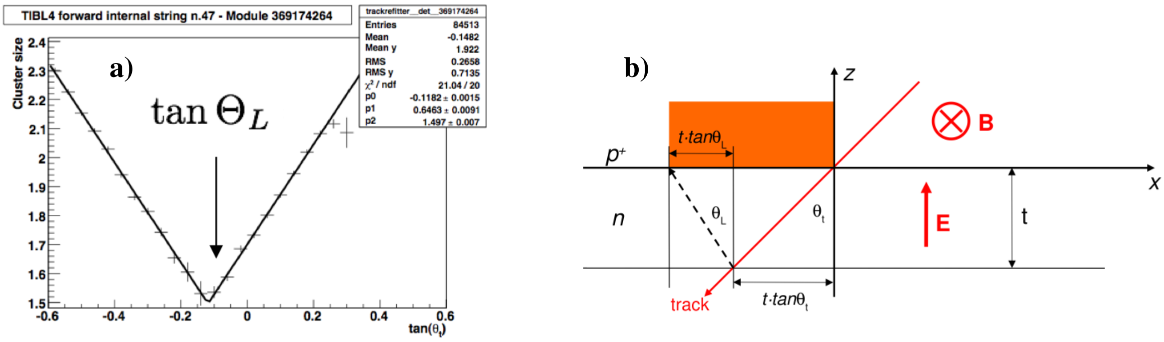

Figure 3: Dependency of the cluster width from the track incidence angle in the plane orthogonal to the strips (a). Schematic model of the cluster formation in presence of a magnetic field for a particle incident with an angle θ_t with respect to the detector normal (b). The cluster size is represented by the rectangle.

The method adopted to measure the Lorentz angle from data exploits the dependency of the cluster width from the track incidence angle in the plane orthogonal to the strips. This dependency is shown in Figure 3 (a), for the clusters reconstructed by a sensor of 500 μm thick with strip pitch of 120 μm, in the CMS 4 T magnetic field. The minimal cluster size corresponds to particles traversing the detectors with the same inclination as the drift lines, as shown by the model in Figure 3 (b). Since the angle between the sensor normal (parallel to the electric field) and the drift direction is by definition the Lorentz angle, the measurement of the track incident angle for which minimum cluster size is achieved provides a direct measurement of the Lorentz angle itself.

The function used to fit the curve is

$$\mathrm{C_W} = \frac{\mathrm{t}}{\mathrm{P}}\mathrm{p_1}|\tan\theta_{\mathrm{t}} + \mathrm{p_0}| + \mathrm{p_2} \tag{3.1}$$

where t is the detector thickness, P is the pitch and $\mathrm{p_x}$ the fitted parameters. The most important one, p_0 estimates the $\tan\theta_{\mathrm{L}}$, p_1 is the slope normalized to the ratio of thickness over pitch and p_2 is the average cluster size in the minimum. In the model the carrier diffusion and the capacitive interstrip couplings are neglected. Actually both these effects contribute to the enlargement of the cluster size, but nevertheless, in first approximation, they do not change the track incidence angle corresponding to the minimum cluster width.

The performance of this calibration procedure has been evaluated with 20 millions of simulated Minimum Bias tracks, equivalent to few days of data acquisition in the LHC startup scenario. The achieved resolution in the Lorentz angle measurement is $\sim$7%, corresponding to an uncertainty less then 5 μm in the reconstructed cluster position. Therefore the accuracy of the approach is good enough for the precision required in the reconstruction.

More details about this method and the associated uncertainties can be found in Ref. [7].

4. The SST DQM system

To ensure that the CMS Tracker system runs smoothly and that good quality data are recorded, the detector performance is monitored using applications based on the CMS Data Quality Monitoring (DQM) framework. The DQM has to guarantee the prompt and efficient identification of any possible problem of the hardware and data acquisition as well as of the reconstruction and calibration, so that actions can be taken at a very early stage. This task is particularly challenging due to the very high SST granularity.

The CMS DQM system creates, dispatches and visualizes the data quality information in the form of histograms. Histograms are defined globally or for individual detector modules depending on the nature and the detail of the information. The DQM system is capable of running on a variety of online and offline environments. In the online mode it can run directly on the CMS Trigger Filter Farm, accessing the Level-1 accepted events at a rate up to 100 KHz, or on dedicated CPUs receiving the HLT selected events and delivered to the monitoring stream at the rate of 1-10 Hz. The online DQM is intended for an immediate feed-back about the quality of the events, and has to match with the limitation imposed by a real-time operation not interfering with the HLT processing. The offline DQM refines the monitoring using all events reconstructed at the offline computing centers.

The SST DQM system monitors all phases of the tracker reconstruction: (i) the raw data monitoring verifies the integrity of the transmitted FED data and checks for possible raised errors; (ii) the cluster monitoring inspects the properties of the reconstructed clusters, as the signal-to-noise ratio, the cluster width, the cluster occupancy, distinguishing clusters either belonging or not belonging to the reconstructed tracks; (iii) the track monitoring examines the reconstructed tracks parameters as momentum, χ^2, number of hits, hit resolution. The histograms are compared to reference distributions using statistical methods. Any discrepancy is promptly pointed out with alarms.

Due to the great complexity of the SST detector the standard DQM tools based on histograms is complemented with two-dimensional graphical images, Tracker Maps [8], that can show the whole information of the detector down to the single channel resolution. This specialized synoptic view of the whole SST is shown in Figure 4, where color-coded detector elements are associable to monitoring quantities or alarm levels. The Tracker Map is interactive, it guarantees an efficient way to store, transfer and display monitoring data through the Web. Any other information accessible via Web, such as histograms, can be easily linked to the individual modules in the Tracker Map.

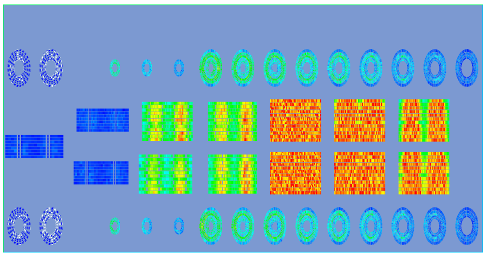

Figure 4: Specialized synoptic view of the whole CMS Tracker, Pixel and SST detectors. Color-coded detector elements are associable to monitored quantities. Here the mean hit occupancy per module is shown in simulated cosmic muon events passing through the CMS Tracker.

5. Conclusions

The outstanding performance of the SST detector in terms of efficiency, purity and resolution in the track reconstruction can be achieved only through a careful tuning of the full system, from the electronic read-out chain to the reconstruction algorithms. Several parameters need to be monitored during the data acquisition and optimized for the processing of the SST data. In this paper an overview of the SST local reconstruction chain has been provided together with a description of the procedures adopted to calibrate and monitor the detector. Due to the very high granularity of the system, these procedures are difficult tasks in the SST operation. Nevertheless the data reconstruction, the calibration work flow and the monitoring tools have been successfully exercised with simulated LHC data as well as with real cosmic muon data[2]. All studies demonstrate that the detector fully meets the design specifications and that the expected performance will be achieved.

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[2] Studies on real data are currently ongoing, based on cosmic muon events collected in the autumn 2008 by the full CMS detector.