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The CMS Inner Tracker Silicon Microstrip Modules: production and test

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Abstract

The Silicon Microstrip Tracker is a key element for the discovery potential of the CMS detector at LHC. The layout of the Tracker and the main components are described. The status of the construction of the Inner part of the CMS Tracker is reviewed. The construction of such a large scale detector requires an industrial and distributed approach. The procedures followed at each step of the production chain are described and finally the tests performed on this subsystem are shown.

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1 Introduction

Physics at the LHC puts severe requirements on tracking detectors, due to the high interaction rate, particle density and received radiation dose. At high-luminosity (10^{34} cm^{-2}s^{-1}), on average 20 minimum bias events are produced per bunch crossing, which will produce more than 1000 tracks in the tracker acceptance, leading to very high detector occupancy. A very fine granularity is needed to resolve nearby tracks. Since the time between bunch crossing is 25 ns, detectors and electronics with fast response time and on-detector pipelined memories to store the data from each collision, until a level-one trigger decision is made, are required. Inner detectors are also required to survive a harsh radiation environment with particle fluxes of between 10^{13} and 10^{14} equivalent 1 MeV neutrons/cm^2/year and they are designed in order to continue working for at least ten years. Furthermore, material in the tracking detectors must be minimised to avoid compromising the calorimeter performance for challenging electromagnetic channels such ad H→ $\gamma\gamma$.

CMS, one of the two general purpose detectors which will be operated at LHC, has been designed in order to explore the full range of physics that can be accessed at LHC. A robust tracking system inside a strong magnetic field is a key element to fulfil this task. The tracker has to be able to resolve and measure precisely all tracks, in order to identify those belonging to interesting interactions. A transverse momentum resolution of 1–2% for 100 GeV/c tracks is required to be able to reconstruct narrow heavy objects and impact parameter resolution of 10-20μm is needed for b and τ tagging with displaced vertices.

To cope with all this stringent requirements, the CMS tracking system features an all-silicon layout consisting of a pixel detector and a silicon-microstrip tracker.

2 The CMS Silicon Tracker

CMS has chosen for its tracking system an all-silicon layout [1], relying on few measurement layers, each able to provide precise and robust coordinate determination. In order to fulfil the requirement on transverse momentum resolution, the tracker is immersed in a 4 T solenoid magnetic field. A sketch representing 1/4 of the tracker is shown in Fig. 1. Going from inside to outside, the tracker is composed by a Pixel detector, providing up to three hits, followed by Silicon Strip Tracker (SST) providing up to 14 hits per track.

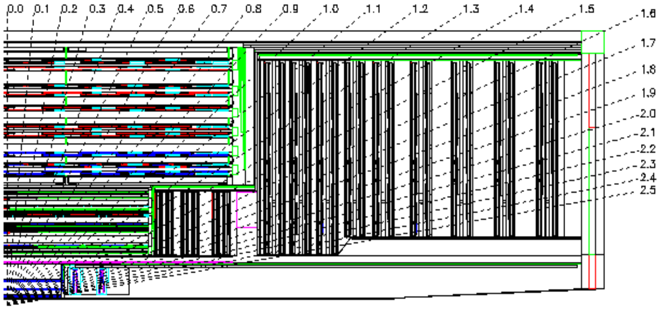

Figure 1: Layout of the CMS Silicon Tracker.

The pixel detector covers the innermost part: three cylindrical barrel layers, located at radii of 4.4 cm, 7.5 cm and 10.2 cm, and two pairs of end-cap disks, located at $|z| =$ 34.5 cm and 46.5 cm, to ensure a coverage up to $|\eta| < 2.2$. The pixel size is 100 x 150 μm^2 and the hit resolution is about of 10 μm in the $r - \phi$ plane and 17 μm in $r - z$.

The SST covers the radial region between 22 and 110 cm. It is divided in four parts. The barrel region ($|z|$ <120 cm) is split into an Inner Barrel (TIB), constituted of four cylindrical layers, and an Outer Barrel (TOB), made of six layers. The TIB is enclosed by three pairs of disks (TID), while the TOB is enclosed by nine End-Cap (TEC) disks ($120 < |z| < 280$ cm), each made by seven rings. The first and second layer of the TIB and the TOB, as well as the first two rings of the TID and rings 1, 2 and 5 of the TEC are instrumented with two sets of single-sided detectors glued back-to-back with a stereo angle of 100 mrad.
Detectors of the TIB, TID, and the first four rings of the TEC are made of a single sensor of 320 μm thickness and have strip lenghts of about 10 cm and pitches of about 100 μm. In the outer part (TOB and the three outermost

TEC rings), in order to reduce the number of channels, the strip lenght and pitch are increased by a factor two, daisy-chaining two sensors. In these regions, 500 μm-thick sensors are used to compensate the increased noise due to larger capacitance. The SST is thus composed of 6136 thin and 18192 thick sensors with an active area of 200 m^2 of silicon and $9.6 \cdot 10^6$ channels. With this fine granularity, the tracker has an average occupancy in the 1% range or below.

The construction of such a large system based on silicon technology has never been experienced before. The enormous effort needed to construct such a complex device has to be faced with an industrial and distributed approach. The CMS Tracker collaboration developed a production chain distributing the work in many laboratories all over the world, keeping the quality at an excellent level and the best possible uniformity among the various centres.

The basic element of the SST is the module. It consists of a carbon fiber support structure, one or two single-sided sensors, with different geometries according to the subdevice they belong to, a capton bias circuit, a pitch adapter and a front-end hybrid, housing four or six chips for signal amplification and buffering (APV), and other chips for module monitoring and trigger control. Fig.2 shows a sketch of a TIB module.

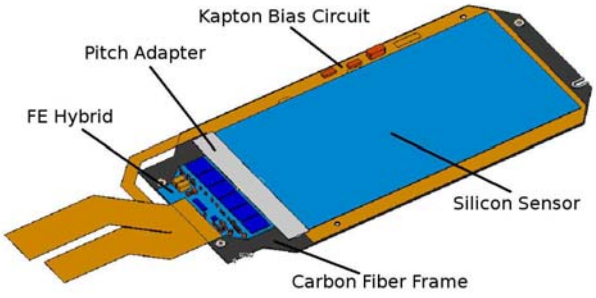

Figure 2: Sketch of a TIB module with its components.

The construction and assembly of the different subsystem (TIB/TID, TOB and TEC) is organized in three different consortia, each made of several different laboratories. The INFN consortium is responsible of the TIB/TID construction and is made by seven different centres distributed all over the Italy (see Fig. 3).

Figure 3: Geographical location of the seven italian laboratories which form the INFN TIB/TID consortium. Bari and Perugia are the two INFN gantry centres; Bari, Catania, Firenze, Padova, Pisa and Torino are bonding and testing centres. In addition, Firenze, Pisa and Torino are also integration centres. See text for more details.

In the following sections, the status of the construction of the TIB/TID modules, as well as the programs for quality assurance on single components and on modules will be described. Finally, the tests performed on the system will be presented. The status of TIB/TID integration is reviewed in [2] while TOB and TEC are reviewed in [3, 4].

3 TIB Module Production Chain

The SST modules are first assembled at the Gantry Centres (Bari and Perugia for the TIB/TID subsystem) and then delivered to the bonding centres (Bari, Catania, Firenze, Padova, Pisa and Torino) where the bias and silicon strip to APV readout bonding are performed. Finally the modules are delivered to Quality Control laboratories in which a full electrical test is performed. Details of each step of the production chain are given below.

The quality assurance for the final modules is crucial. A peculiarity that has to be taken into account for TIB/TID modules is the difficulty to replace them once they are integrated into the final mechanical structures. For this reason the test procedures to qualify each single TIB/TID module are very demanding in terms of defect finding and reliability.
Production centres have, as much as possible, identical equipment, software and procedures. In addition, results from tests at all stages are stored in a central database, to allow monitoring of the production quality and quick feed-back to production centres.

3.1 Module Assembly

The mechanical assembly is realized with an accuracy of few tens of microns, together with a high uniformity between multiple centres, thanks to the usage of the semi-automatic Aerotech Gantry Machine [5].
Module components are placed on a plate providing motion in 3 linear and 1 rotational coordinates; a software-driven arm is equipped with a CCD camera and a syringe to dispense the glue. The mechanical precision of the modules is checked before and after glue curing, measuring the position of fiducial marks on sensors with respect to precision pins on the support frame. A pattern recognition software is used to locate the fiducial markers placed on the module components. Fig. 4 shows the results for the TIB assembled modules. The quality parameters are the distances in the x and y coordinates and the angle tilt between the sensors and the carbon frame. The RMS of the produced modules is less than 10 μm in $|\Delta x|$ and about 6 mrad in $|\Delta\theta|$.
The system can assemble modules with the required precision and almost without operator intervention with a production rate of the order of 18 – 24 modules per day per each centre.

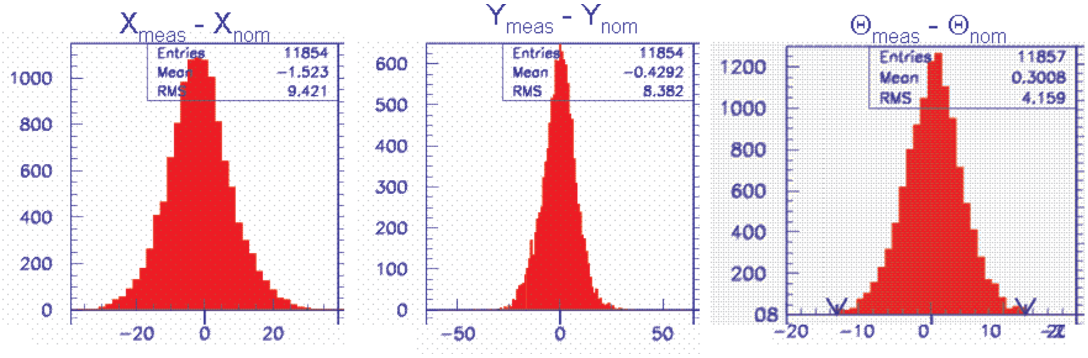

Figure 4: Gantry quality parameters: Δx (left), Δy (middle), $\Delta\Theta$ (right).

3.2 Module Bonding

Preassembled modules are sent to the bonding centres. Six bonding centres are currently in operation in the TIB/TID community. Each centre is equipped with an automatic wire bonding machine, which is used to perform the bonding between silicon strips and pitch adapters as well as the bias bonding. The first action taken at module arrival at the bonding centres, is an accurate optical inspection of each module under a microscope searching for possible visible damages. After the optical inspection a first electrical test, called "Rapid Test', of the module (hybrid and pitch adapter only, since at this stage the sensor is not connected to the front-end electronics) is done using a compact standalone system called ARC [6]. This test consists of a "Fast Test" used to spot gross anomalies in a few seconds, followed by a more accurate "Deep Test' which consists of a pedestal, a calibration pulse shape and a pipeline run. The purpose of these tests is to check the integrity of the preassembled module after the transport and before the sensor microbonding. Almost 100% modules pass this test and are then bonded.
Since the microbonding of the detectors is a delicate operation, tests on the strengths, deformation and lift-off are done on test pads of the pitch adapters. In addition, pull tests are done, on a sample basis, to have a quality control of the bond strength. The force at which the bonds break is required to be larger than 5 grams. All

centres demonstrated pull forces well beyond the required threshold, with a good uniformity between the different laboratories.
A total of about 2.5 Million bonds has been realized, which correspond to almost the 98% of the bonding production for the whole TIB/TID system, with a unrepairable failure rate of 0.01%.

3.3 Module Full Test

After the bonding, modules are delivered to Quality Control laboratories.

According to the quality specifications required in order to have efficient tracking capability, the modules should have a number of defective strips below 1% (Grade A) or 2% (Grade B). Modules with more than 2% bad strips (Grade C) are discarded. Furthermore if the module is not able to reach the maximum voltage of 450 V with a current lower than 10 μA, it is deeply investigated and, if the problem is not easily solved, it is rejected. TIB/TID modules must also pass a "Long Term" test (LT) to detect defects or failures developed in the first period of functioning (early mortality) and validate the performance of the module at low temperatures.
To match these requirements two different test setups have been used: the ARC system [6] and the LT system [7]. While the former is used to quickly test a single module in the different stages of the production chain, the latter is a complex system used to continously readout a batch of modules (up to ten) while thermal stresses, similar to the real CMS Tracker operating conditions, are being applied.

In order to quickly identify and possibly correct module problems a full electrical test is done just after the bonding. The module is connected to the ARC system keeping it under a shielding clamshell in a dry (relative humidity less than 30%) atmosphere and a full set of tests is performed: a full sensor I-V curve up to 450V, a pedestal, noise and pulseshape run in order to detect open, noisy or shorted neighbouring channels and a pinhole identification by means of light-induced sensor leakage current. A pinhole is a short or ohmic connection between the aluminium strip and its corresponding p$^+$ implant, and is potentially the most dangerous defect, since it can prevent the whole chip to properly work. All the informations coming from the full test are stored in a ROOT[8] file and are kept at each testing centre for future reference; the most relevant information about the status of the module are also saved to the central Tracker construction database. The ARC full test can be done in less than half an hour. When necessary the module is sent back to the microbonding machine operator for fast repairing and then retested.
The strategy adopted to classify the defects is based on the different behaviours of defective channels; combinations of anomalous values of CMS (common mode subtracted) noise, calibration peak time and pulse height are used to distinguish between different kind of defects. Two types of failures can prevent module to pass the I–V test: resistive behaviour, usually related to sensor scratches or electrical defects, and the occurance of breakdown at voltage lower than 450 V.
Fig.5 (left panel) shows the I–V of all the TIB modules produced up to this date. While the majority of the modules shows a regular behaviour, modules with resistive behaviour or low breakdown are clearly distinguishable. Fig.5 (right panel) shows the noise pattern for a module with eleven defects. About 2% of modules are rejected at this stage.

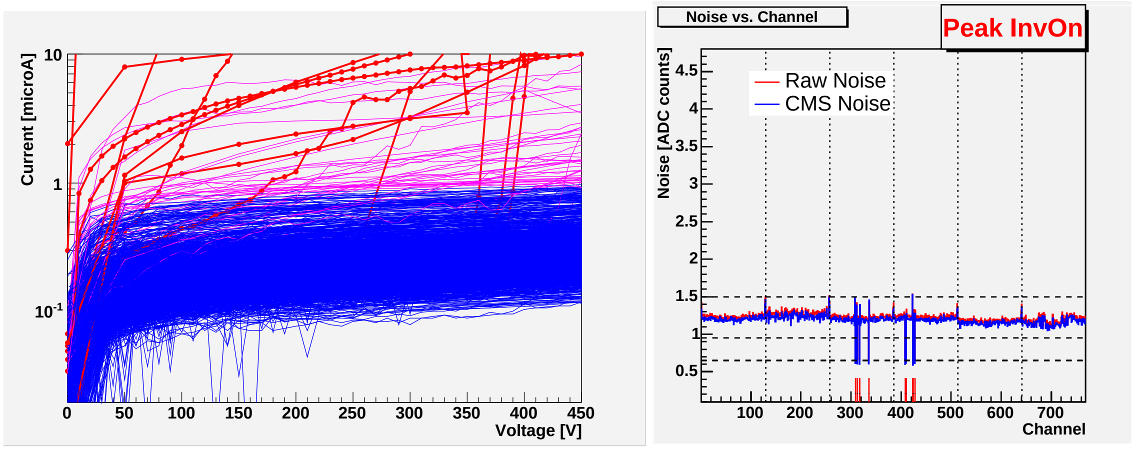

Figure 5: Left:I–V curve for almost the whole TIB module production. Modules with bad I–V behaviour are clearly distinguishable. Right: Noise pattern of a TIB module with several defects.

After the ARC test, all modules have to pass a long term test. The LT setup is based on a climatic chamber which can host up to ten modules mounted on their support plates and a complete readout chain based on components similar to the ones used by the final Tracker DAQ system. The test duration is of the order of days (two to three) with thermal cycles ranging between +20^{o}C and -20^{o}C (low end operational temperature in CMS Tracker). To avoid dangerous ice or water condensation on the modules the chamber is flushed with dry air or nitrogen and the relative humidity is continuously monitored. While the modules are thermally cycled they are always powered and readout almost continuously. Their behaviour is monitored during the full test duration, in particular at low temperatures. At this stage of production those modules are kept for the first time to the standard operating temperature in the CMS Tracker. A “Long Term scenario” includes sets of standard measurements (pedestals, noise, calibration, taken in all four APV modes and IV curves) at +20^{o}C and -20^{o}C, together with continuous pedestal and noise measurements during cooling down and warming up periods. All Long Term test measurements are stored in a ROOT file and, as for the ARC test, the most relevant informations about the status of the module are saved into the Tracker construction database.

Less than 1% of modules are rejected because od defects appeared during the thermal cycle stress.

4 Conclusions

The tracking system of the CMS detector will be fully based on silicon technology. The layout of the detector has been optimized in order to match the expected performances. A detailed organization with an industrial and distributed approach has been realized for the construction of such a large-scale detector, in order to guarantee a uniform quality and match the schedule. A high uniformity between the laboratories has been achieved, with an excellent quality: as of February 2006, the TIB and TID modules are almost completed. About 3% of modules are rejected, with about 0.1% of bad strips found on good modules. Integration in substructures has already started and proceeds in time to match the foreseen schedule.

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