Status of the integration of the Tracker Inner Barrel of CMS

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Abstract

The CMS Silicon Strip Tracker is the largest tracking system made of silicon devices ever built for a High Energy Physics experiment. Such a complex detector required a long period for the production and qualification of each component and a system test to verify that the expected performance is met. The Tracker Inner Barrel (TIB) is the central sub-detector consisting of four cylindrical layers centered around the beam pipe. The status of construction of the TIB will be described, focusing on the procedures defined to assemble the hardware components and on the tests performed during the integration to check for their functionality. The database system used to select components and keep track of them is also briefly described. The performance of a TIB subsystem read out with the final DAQ have been analysed in different operating conditions and preliminary results are presented.
1 Introduction

The CMS collaboration is building a multipurpose detector[1] optimised to explore the physics potential of the CERN Large Hadron Collider (LHC)[2]. In order to fully investigate different signatures of physics events produced in proton-proton collisions, a good detector for track reconstruction and pattern recognition is required. The CMS Tracker[3] designed to fulfill such requirements is based on two different technologies, silicon pixel and silicon microstrip detectors. The layout of the CMS Tracker is sketched in figure1: the innermost part is made of pixel detectors to provide three-dimensional space points in the high particle density region, while the outer Tracker volume is instrumented with microstrip detectors and is referred to as the Silicon Strip Tracker (SST). The SST is a large and complex detector, with a total active area of about 200 $m^2$, organised in four regions: the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Outer Barrel (TOB) and the Tracker End-Cap (TEC).

This paper presents the status of the Tracker Inner Barrel, focusing on the construction and integration phase. After a brief review of the TIB design, a detailed description of the assembly procedure is given. The integration activity is presented together with the tests performed to check the functionality of detectors and hardware components. Results from such measurements are discussed to show the performance of TIB layers. A final test on the fully assembled sub-structure performed in similar conditions to the CMS Tracker operation is presented. This test is done in a climatic chamber using the final DAQ and power supply system to validate the structure. Preliminary results from this system test are also reported.

2 Tracker Inner Barrel

The Tracker Inner Barrel is the inner sub-detector of the SST and consists of four cylindrical layers centered around the beam pipe. These layers are made of a carbon fiber supporting structure with modules mounted on both sides of the cylindrical surface to minimise dead regions. A total number of 1956 modules are used to equip the TIB

| Layer # | # of modules | type |
|---------|--------------|------|
| 1       | 336          | DS   |
| 2       | 432          | DS   |
| 3       | 540          | SS   |
| 4       | 648          | SS   |

Table 1: Total number and type of modules used for each TIB layer. SS and DS represent single-sided and double-sided module. The two innermost layers are equipped with double-sided modules to provide three dimensional information, while the external ones are instrumented with single-sided modules. Each module is made of a carbon fiber support frame to which a single sensor is glued. Sensors used for TIB modules are 320 $\mu m$ thick $p^+$ on n-type substrate microstrip detector produced by HPK (Japan)[4]. Two different designs are used: 768 strips sensors with 80 $\mu m$ pitch in the first two layers which are closer to the interaction region and 512 strips devices with 120 $\mu m$ pitch for the TIB external region where the track density is lower. A detailed description of sensor designs is given in [5]. Single-sided modules are built with sensors having the strips parallel to the beam direction to measure the $r$-$\phi$
coordinate. The double-sided modules consist of two single-sided detectors glued back-to-back, the first one used for the \(r-\phi\) coordinate and the second one with strips tilted by 100 mrad to measure the \(r-z\) coordinate. All non-faulty sensor channels are connected through a glass pitch adapter to the front-end electronics. The readout is based on the APV25 ASIC [6] built in radiation hard 0.25 \(\mu\)m CMOS technology. Two operation modes are available: peak and deconvolution. In peak mode, only data sampled at the peak of the signal are processed, while in deconvolution mode three samples are summed with appropriate weights in order to reconstruct single bunch-crossing information. Each APV accepts 128 inputs and time-multiplexes them on a single output. The analog data of two adjacent APVs are further multiplexed on the hybrid and converted to optical signals via Analogue Opto Hybrids (AOH). The signals are sent through fibers to the Front End Drivers (FED) boards which provide opto-electrical conversion, digitization, pedestal and common mode subtraction.

The system for the readout and control of modules is sketched in figure 2. The smallest readout and control unit is called a “string”; it consists of three single-sided or double-sided modules connected by a mothercable with a Communication and Control Unit (CCU) which provides 40 MHz clock, trigger and communication to modules with \(I^2C\) protocol. Mothercables are also used for low and high voltage distribution to modules. A group of CCUs and thus of strings are connected in a token-ring configuration, referred to as control ring. The control is handled by the Front End Controller (FEC) which communicates via an optical link with the CCU. In order to prevent any problem due to the loss of a CCU that would break the ring, an additional set of connections is used to implement a second redundant ring. More details on the readout system designed for the CMS tracker can be found in [7].

Such a huge detector required quite a complex organization for the full qualification of all components and for the final assembly of modules. This work has been shared by several INFN\(^1\) laboratories. The assembly of TIB layers is done in two centers, Pisa and Florence, while the final integration task will be done in the Pisa laboratory. A strong effort has been performed to automatize the test of module components to ensure their full qualification within the available schedule. This activity was also needed to provide a constant feed-back to companies involved in the production of components to discover any problem in the fabrication process and find solutions in as short a time as possible.

The assembled modules are tested for final qualification and grading [8]. A full test is done to check for functional problems and to identify all defective channels. A long-term test is then performed in a climatic chamber to verify the performance after multiple thermal cycles between room temperature and \(-20^\circ C\). All data are stored in the CMS tracker construction database to be accessed at any time.

The module production and qualification activity is currently completed. The results of the qualification tests are fully satisfactory: more than 96% of the modules fulfill the selection parameters defined by the collaboration for the final acceptance, and the overall quality of accepted modules is excellent (> 99.9% active strips).

\(^1\) National Institute of Nuclear Research (Italy). The laboratories involved are: Bari, Catania, Firenze, Padova, Perugia, Pisa, Torino.
3 Integration of the Tracker Inner Barrel

The schedule defined for the optimisation of the TIB subdetector assembly foresees the construction of the forward part first, corresponding to the positive z direction; the backward region will be integrated just after completion of the first half.

The procedures of assembly and integration of both parts are similar and have been standardized with the experience gained working on a prototype structure.

The integration procedure has been simplified by dividing each cylinder in two symmetrical parts which will be independently assembled, surveyed and tested in two different laboratories. The carbon fiber shells have been produced by the Plyform company (Italy) and qualified by the TIB engineering group. The mechanical structure is initially equipped with cooling pipes to maintain the tracker volume at the working temperature of $-10^\circ$C. Precision ledges are then glued onto the structure to define the module positions and guarantee a good thermal contact for the most critical elements. The structure is completed with the gluing of pillars for the interlayer connection.

Once the cylinder is ready for the module assembly, a geometrical measurement of the structure is done using a coordinate measuring machine to survey the position of the modules in space.

A dedicated database system has been designed for the TIB construction to provide the geometrical position of all components mounted on the structure, the connectivity description accounting for all device and pipe connections, and to store the results of electrical tests performed on the assembled devices. It is also used to make an automatic selection of modules to be mounted on the structure on the base of the operating voltage and its foreseen evolution with radiation damage.

The integration procedure includes different action steps: fiber threading and AOH mounting, Digital Opto Hybrid cabling and control ring test, mother-cable insertion, mounting of modules and final cabling.

Once the mechanical structure is ready for integration, the assembly of AOHs starts. Optical fiber handling and routing is a delicate task and silicone protection spirals have been adopted to prevent damage to the fibers.

Before mounting the modules, cabling for the control ring is implemented to reduce risks for modules during this operation. At this stage some tests on the control rings are performed such as CCU communication and control ring redundancy. If any problem is discovered, the defective hardware is replaced to have the final control system working properly. When the control rings are completed, mechanical supports and all connected cables are removed from the structure to make easier the operation of module assembly.

After the insertion of a mothercable in the string, modules are removed from their support frames, registered in the integration database and mounted on the structure. Module assembly is a delicate operation done by trained operators using a controlled torque screwdriver to tighten four tiny screws which, together with one precision pin, hold the module in its position. Modules are then connected via the control, high voltage and AOH connectors.

Once a string is completed, a test is done to check functionality and replace any faulty module before adjacent strings are assembled. Two different types of tests are done: a purely digital test to check communications with all components through the I$^2$C protocol, and a full test with modules biased at 400V to study the noise performance. Collected data are analysed with an automatic tool which handles also the storage of data, the match with database information from previous tests, and the production of some plots on the noise performance for a preliminary check.

For each module, a comparison on the number and position of bad channels with data stored in the database is done to check the consistency with module test qualification data. As an example, figure 3 shows the strip noise for a single-sided module before and after the common mode noise subtraction. A comparison with the expected number of bad channels and their position is also included. In case of operational problems, the problematic module is dismounted from the structure and replaced with a new one.

A global analysis of the substructure performance can be done by summing up all the single module noise data. Figure 4 shows the strip noise distribution for all modules mounted on one half of layer four using the deconvolution readout mode. The noise performance is very good, as expected from module test results. Only a few noisy strips and a negligible fraction of open channels are observed, in agreement with the module qualification data. The total number of defective channels is below 0.1%.

The overall activity of TIB integration is progressing well. Only a few problems were encountered during the assembly. A few AOHs have been replaced due to broken fibers, probably damaged during handling before the use of silicone spirals. A few modules have been also replaced for different problems: on a total number of 574 modules 2 have been replaced for damage on the microbonds and 3 for low breakdown voltage, probably related to the high humidity level in the clean room during the test.

Such good results indicate a proper handling of all components and confirm the validity of the qualification procedure defined by the CMS Tracker collaboration.
Figure 3: Module strip noise before and after common mode subtraction. List of bad channels is compared with module test data.

Figure 4: Superimposed strip noise distribution of 156 modules mounted on half layer 4 readout in deconvolution mode.
4 System test

A final test is done on each assembled half-cylinder to validate the structure in conditions similar to the CMS Tracker operation. Measurements are performed in a climatic chamber which reproduces the Tracker operating temperature of $-10^\circ$C. The tests are done with the final power supplies and cables and a final DAQ system is used to read-out the whole structure.

The procedure consists in a run with temperature cycles to monitor the stability of power consumption, temperatures and performance. It also represents an excellent opportunity to study in detail some system aspects of this complex structure, mainly for grounding optimization.

The cooling system is based on a circulating fluid, the temperature of which is regulated by a chiller. Measurements are done at two different temperatures, +10 and -25°C. Temperatures on sensors and hybrids are monitored using the information from the Detector Control Unit, a chip which is placed on the front-end hybrid that provides also informations on currents and voltages. The measured temperature values of sensors and hybrids are well within expectation for non-irradiated devices. A cross check of the uniformity of the temperature distribution is used to identify modules in bad thermal contact with the cooling system. An independent measurement on temperature and humidity is done with dedicated sensors glued on the structure and used by the Detector Safety System.

A typical run includes different steps: first a timing adjustment is done, to align the arrival time of digital tickmarks on the front-end electronics. Then the AOH gain adjustment is performed to optimise the laser settings. The next action is the baseline adjustment, looping over the VPSP settings for each APV. Finally, a pedestal run is done to calculate pedestal and noise before and after the common mode noise subtraction.

The strip noise distribution for all modules mounted on the structure and readout simultaneously is shown in figures 5 and 6. Measurements are done in both readout modes: figure 5 and figure 6 shows data taken in peak and deconvolution mode respectively.

The noise performance of the half-cylinders of the external layers 3 and 4 are very good: the observed noise levels agree with the most favourable expectations. An average value of about 3 ADC counts in peak mode and 4 in deconvolution mode has been measured. A comparison with TIB results from the analysis of 2004 test beam data indicates a signal-to-noise value of about 20 in deconvolution mode. An “in-situ” check of this preliminary estimate using cosmic rays data is underway.

5 Conclusion

The integration phase of the CMS Tracker Inner Barrel is progressing well. The construction of two TIB layers, namely layers 3 and 4, has been completed. Integration of layer 2 has started.

The assembly of components and modules onto the mechanical structure was successful as confirmed by the excellent results on the performance of the assembled modules. The number of defective channels is very low and compatible with single module test data.
Figure 6: Noise distribution in deconvolution mode of one half-cylinder of layer four readout with the final tracker DAQ system.

A system test on the integrated structures was performed using the final cabling, DAQ and power supply system. Such measurements done in a climatic chamber to reproduce the experimental working conditions of the tracker proved the good performance of the first two forward layers and confirmed the validity of integration procedure used for the TIB construction.

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