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The CMS Silicon Strip Tracker

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Abstract

The CMS strip tracker is the first large scale tracker entirely based on silicon detectors technology. It consists of 198 m^2 of detector sensitive area instrumenting the inner region of the experiment with a pseudo-rapidity coverage of $|\eta| < 2.5$. This instrument, together with a silicon pixel system, is expected to perform robust tracking and detailed vertex reconstruction while embedded in the LHC high radiation and high luminosity environment. The project is in a well advanced construction phase: the detector module production is completed, the integration of the single components into large sub-detector units is underway and the full tracker commissioning is about to start.

In this paper, after a description of the tracker layout, a detector modules production overview and a summary of the integration procedures for the inner barrel part of the tracker will be reported.

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1 Introduction

The CMS silicon strip tracker [1] is a complex detector whose dimensions can be clarified by a few numbers: 21 m^3 of instrumented volume, 15 148 silicon strip modules, 9 316 352 analogue readout channels, $-10\,^oC$ sensor operating temperature, radiation fluence up to 1.6×10^{14} 1 MeV equiv. neutrons/cm^2 for an expected lifetime of about 10 years at the LHC. The realization the tracker is based on the availability of high technology single components and their assembly into large sub-detector units with performances unaffected by the system complexity.
The silicon strip sensors used are single sided “p+ on n” type, with metal over-hang implemented to obtain high breakdown voltages and $< 100 >$ crystal orientation to minimize the surface radiation effects [2][3][4]. The silicon detector front-end chips [5] are realized in 0.25 μm CMOS technology: the thin gate oxide together with special layout techniques ensure their radiation tolerance [6]. The assembly of the detector modules has been carried out using automatic machines [7] with a high mechanical precision and reproducibility. The modules quality has been monitored by extensive functional tests, performed also at realistic final working temperatures, which have characterized each single strip of the whole production set and spotted out problematic components.

2 The CMS Silicon Strip Tracker Layout

The CMS Silicon Strip Tracker occupies the radial range, around the LHC interaction point, between 22 cm and 110 cm [8]. The central region ($|z| < 110$ cm$^{1)}$) is split into an Inner Barrel (TIB), made of four detector layers, and an Outer Barrel (TOB), made of six detector layers. The TIB is shorter then the TOB, and is complemented by three Inner Disks per side (TID) each made of three rings. The forward and backward regions 120 cm $< |z| < 280$ cm are covered by nine End-Cap (TEC) disks per side, each made of seven rings. The two innermost layers of both TIB and TOB as well as rings number one, two and five of TEC and one and two of TID are realized with double-sided detector modules. The whole tracker region is embedded into the CMS 4 Tesla solenoidal magnetic field, a charged particle transverse momentum resolution of about 1.5% for central muon of 100 GeV/c is expected [9].

3 Detector Modules

The detector module design has been kept as simple as possible to ease their mass production and integration. The sensor is glued on a carbon fibre support frame which also holds the front-end electronics hybrid. The readout chip pitch (44μm) is matched to the sensor pitch via a glass fanout circuit (pitch adapter). The hybrid circuit, which houses the front-end chips and ancillary electronics, is realized using kapton multilayer technology. Figure 1 shows a single sided TIB detector module.

Detectors of the TIB, TID, and of the four innermost rings of the TEC have strip lengths of approximately 12 cm and pitches between 80 μm and 120 μm. These detectors are made of a single sensor 320 μm thick. In the outer part of the tracker (TOB and three outermost TEC rings) strip length and pitch are increased by about a factor of two with respect to the inner ones. In order to compensate for the noise increase due to the higher inter-strip capacitance (longer strips), a silicon thickness of 500 μm has been chosen for these larger detectors.
All Silicon Strip Sensors are of single sided type. Double sided detectors are realized simply gluing back to back two independent single sided modules: to obtain a coarser but adequate resolution on the longitudinal coordinate the so called “Stereo” module has the sensor tilted of 100mrad with respect to the “R-Phi” one. The “Stereo” sensor and electronics are identical to the “R-Phi” ones, the only difference being in the support mechanics and pitch adapters.

4 Tracker Electronics

The signals coming from each strip are processed by front-end readout chips (APV25) mounted on a multilayer kapton hybrid circuit. The APV25 is a 128 channel chip built in radiation hard 0.25 μm CMOS technology. Each channel consists of a preamplifier coupled to a shaping amplifier which produces a 50 ns CR-RC pulse shape. The shaper output of each channel is sampled at 40 MHz into a 192 cell deep pipeline. The pipeline depth allows a programmable level 1 trigger latency of up to $4\mu s$, with 32 locations reserved for buffering events awaiting readout.

[1)] z is the coordinate along the LHC beam axis

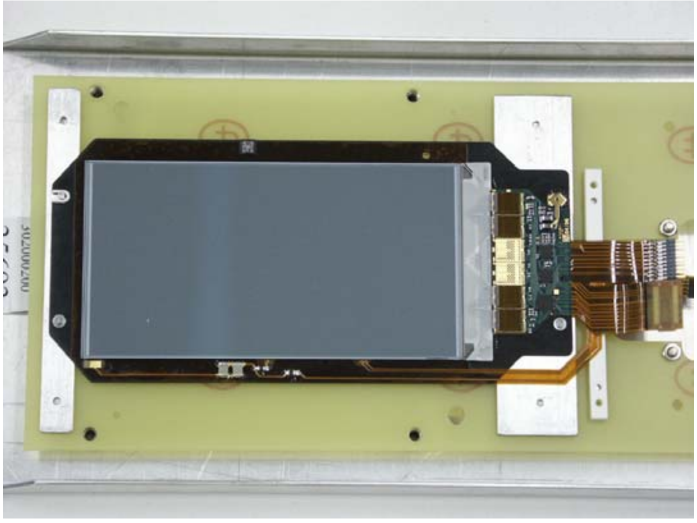

Figure 1: A TIB single sided module fixed on its transportation cradle.

Each pipeline channel is read out by an analogue circuitry which can operate in one of two modes. In peak mode only one sample per channel is read (timed to be at the peak of the analogue pulse shape). In deconvolution mode [10] three samples are sequentially read and the output is a weighted sum of all three. The deconvolution operation results in a re-shaping of the analogue pulse shape to one that peaks at 25 ns and returns rapidly to the baseline. This operating mode is particularly important for correct bunch crossing identification during the high luminosity running phase of the LHC. A unity gain inverter is included between the preamp and shaper which can be switched in or out.

On receiving a positive level 1 trigger decision the APV25 sends out serially, at 20MHz rate, the 128 analogue signals together with information about the pipeline address and the chip error status; signals coming from two APV25 are interlaced together on a differential line by a Multiplexer chip which is located on the hybrid circuit too. The electrical signals are then converted to optical ones in dedicated Analog-Opto Hybrids (AOH) few centimeters away from the detector, and transmitted to the counting room by means of multi-mode optical fibres [11], where they are digitized [12]. The LHC 40MHz clock, which drives the APV25 sampling can be synchronized at the single module level by means of a PLL (phase lock loop) chip. The entire readout chain is able to sustains a level 1 trigger rate of about 100KHz. The functional parameters of the devices located inside the tracker can be downloaded from outside using the I^2C standard communication protocol.

5 Module Production and Test

The different module components (silicon sensor, support frame, front-end hybrid with pitch adapter and HV bias circuit) are glued together using automatic assembly machines. After gluing the modules are shipped to the bonding and test centres where they are micro bonded using industrial wire bonding machines. The quality of this operation is monitored measuring, on a sampling base, the bond pull strength.

During the production chain the modules are subjected to a certain number of functionality tests which aim to verify the detectors quality and reliability finally certifying them for integration into the tracker. The module qualification procedure is mainly done, at room temperature, using a single module test station ("ARC" [14]). For TIB, TID and TOB a long duration thermal test, using a multi module setup, is also done.

A bonded module is tested by the ARC system performing:

- fast functionality test;
- IV characteristics measurement;
- pedestals, noise and internal calibration runs at 400V bias;
- LED test.

The first test checks the module basic functionalities: front-end chip response to operational parameters downloaded via I^{2}C line, normal low voltage consumption, fast noise and calibration response. The IV curve is measured up to 450V: a module is rejected if it is not able to reach the maximum voltage or the current is higher than $10\mu A$ per sensor. Figure 2 shows the bias current measured at 400V for almost 3000 TIB modules; the bias current limit excludes $\sim$ 2% of the TIB modules.

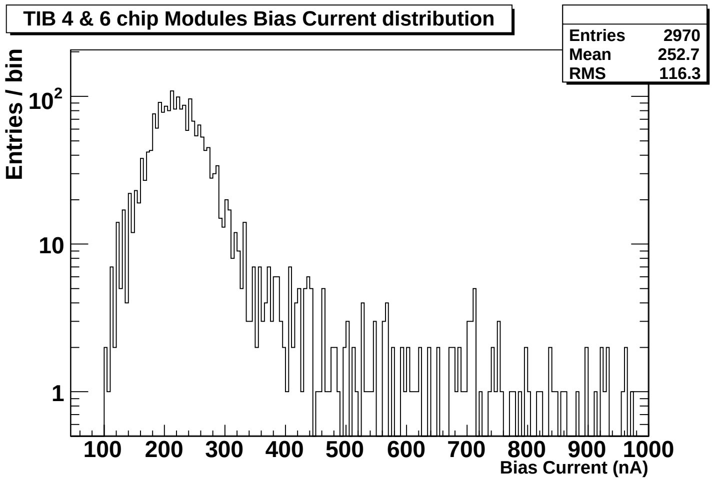

Figure 2: Bias current distribution measured at 400V for TIB modules by the ARC system.

The third test is performed in the four different front-end operating modes: peak, deconvolution, both with inverter on and off. In such a way dead, noisy and shorted channels are selected using the common mode subtracted noise and the internal calibration amplitude and timing. Qualitatively dead channels have low noise and almost zero calibration amplitude, noisy ones have higher noise, while shorted have higher noise and low calibration amplitude (typically half of the normal because the injected calibration charge is shared between two shorted amplifier inputs). Figure 3 shows an example of cumulative noise measurements for TOB single sided detectors. Disconnected or "dead" channels have noise less that 1.7 ADC counts while noisy channels have noise values greater than 2.5 ADC counts.

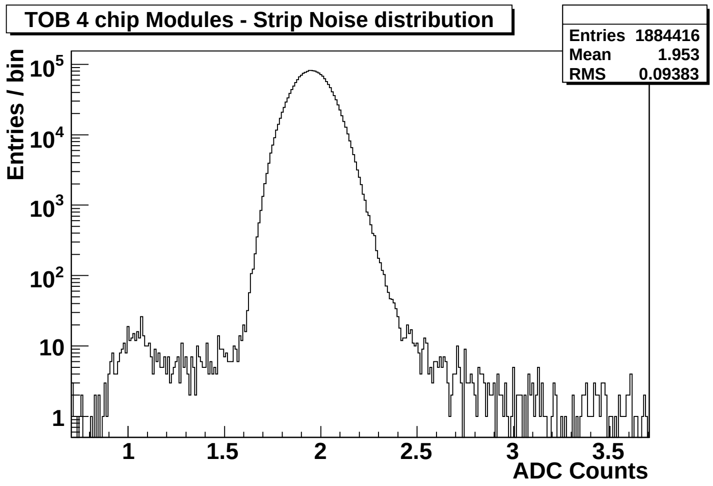

Figure 3: Single strip common mode subtracted noise for TOB single sided modules (ARC system, 400V bias voltage, deconvolution mode inverter on).

Finally an LED device artificially increases the sensor bulk current in order to identify possible implant-readout strip shorts or "pinholes". In fact, when implant and read-out strips are shorted together, a high bias current flowing through the 1.5 MΩ strip bias resistor can move the amplifier input working point away from its normal range resulting in an anomalous response of the channel to the internal calibration pulse. To prevent problems to

	Module Produced	Good after tests	Bad	Yield %
TIB/TID	3945	3810	135	96.6%
TOB	5434	5348	86	98.4%
TEC	7228	6761	467	93.5%
Total	16607	15919	688	95.9%

Table 1: CMS Tracker Silicon Microstrip Module production statistics.

the APV25, strips identified as "pinholes" are disconnected from the electronics.

Defective strips identified by the ARC system should be less than 2% otherwise the module is rejected. The accepted modules are classified into two categories: "class A" if the bad strip number is less than 1%, "class B" if it is between 1% and 2%. Figure 4 shows the number of bad strips per module in the TIB double sided detectors: 71.2% of the production is defect free, while 15.1% have only one (out of 768) bad strip per module and 13.7% have more than one bad strip.

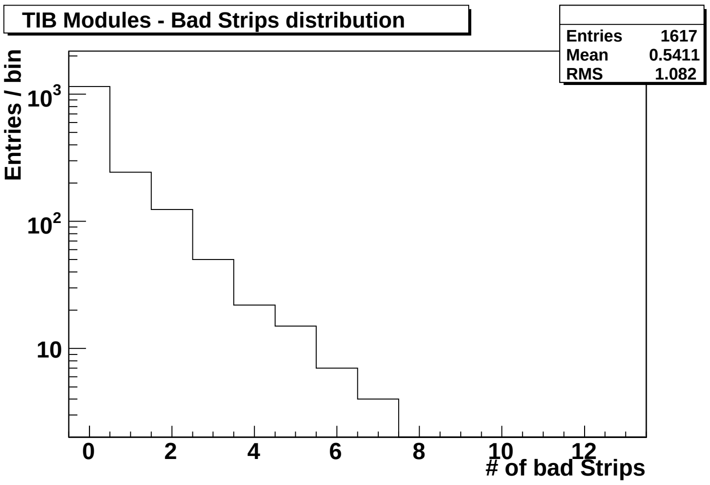

Figure 4: Bad Strips per module distribution for double sided TIB modules.

If the ARC test is passed a module is tested at a temperature similar to the real detector conditions. Up to nine modules are inserted in a climatic chamber which thermally cycles them between $-15\,^oC$ and $+20^oC$ in a dry atmosphere. During these cycles, which duration is between 12 and 72 hours, the module is readout and IV, pedestals, noise and calibration measurements are done. This "long term test" is aim at identifying weak module components which can possibly break early in the detector lifetime.

All the information extracted from the ARC and Long Term tests are stored into the tracker construction Data Base. The final module production statistics is summarized in table 1.

6 TIB Integration

The integration of module, electronics, mechanics and services all together to finally arrive to the setting up of the complete tracker has started and it is now in a well advanced stage. In the following the TIB integration procedures will be summarized.

The TIB modules are directly assembled into "half cylinder" shaped large structures (or "shells") each of them containing several hundreds of different components. On the contrary TOB and TEC proceed through an intermediate step where modules and services are assembled into "rods" and "petals" which are then used as building blocks for the assembly of the sub detectors.

The TIB integration begins from the carbon fibre mechanics, where the aluminium cooling pipes and the precision ledges for module mounting and cooling have been already glued on both inner and outer surfaces of the shell. This structure, supported by an aluminium frame and complemented by boxes to temporary hold the optical fibres, is mounted on a bench which allows to rotate the half cylinder along its longitudinal axis for better accessibility.

The AOH are the first components to be mounted on the structure; the two meters long optical fibre tails are fixed on the carbon fiber and routed outside where they are stored on the temporary boxes. Then kapton auxiliary circuits, which provide the three modules on a string with clock, trigger, control signals as well as LV and HV power lines, are inserted below the supporting ledges. The structure is now ready to accepts modules which are manually mounted on the ledges. The precision and reproducibility of the module positioning are guaranteed by pins and inserts which fix the module frame position with respect to the ledges. Figure 5 shows a string of single sided modules mounted on the inner surface of a TIB shell; AOH with their optical fibres, cooling pipes and precision ledges are also visible.

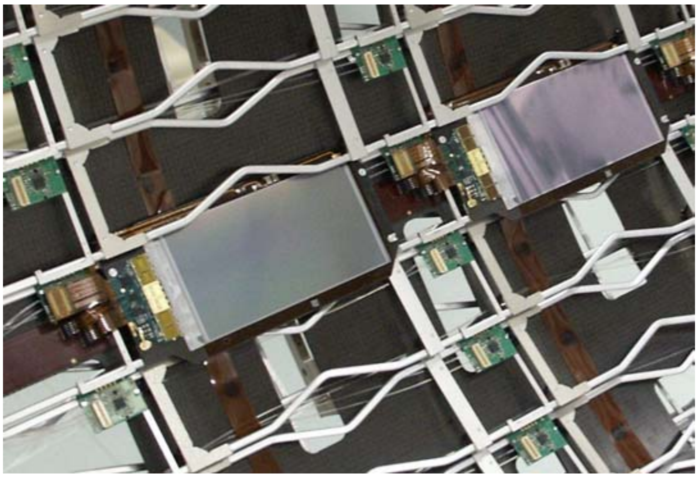

Figure 5: A string of modules mounted on the inner surface a TIB shell (layer 4).

Dismounting a module, in particular a double sided one, when a shell is completed it's a potentially dangerous operation for the adjacent strings. To reduce at a minimum this risk a full functionality test is performed as soon as a string of three modules has been mounted. The I^2C communication and the modules identity are verified and a noise run, at 400V bias, is taken and immediately analyzed comparing the results with the defect list extracted from the module production database. Figure 6 shows a TIB layer 3 shell with modules and services mounted on both inner and outer surface.

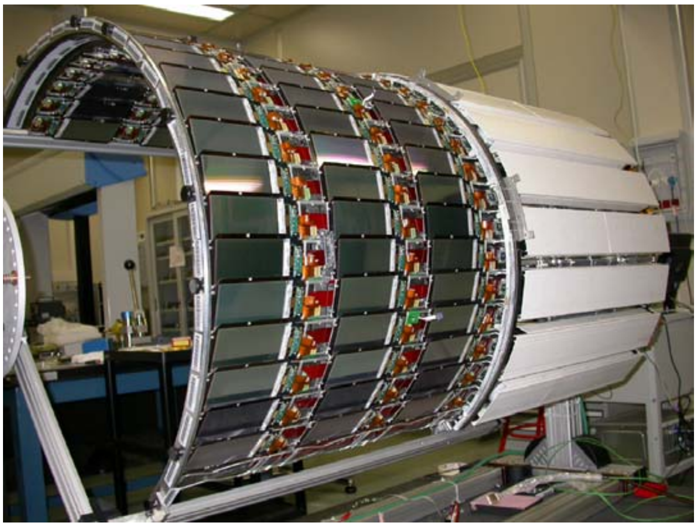

Figure 6: A TIB layer 3 shell on the integration bench.

The TIB control electronics, which distributes clock, trigger and I^2C signals to the modules, is located on a carbon fiber support mounted on the shell external surface just above the modules. This is the last component to be installed and cabled before a final test is done. Figure 7 shows the cumulative strip noise distribution of the 159 single sided modules mounted on a TIB layer 4 shell.

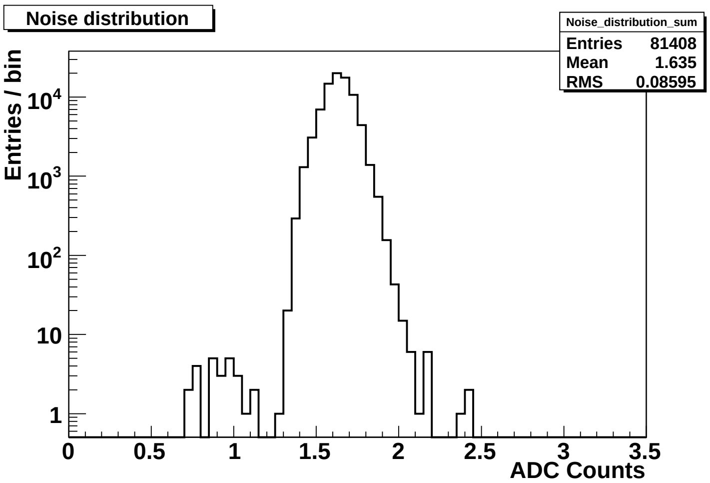

Figure 7: Single strip noise for the 159 TIB modules assembled on a TIB layer 4 half cylinder (400V bias voltage, deconvolution mode inverter on).

When the integration is completed the shells are sent to the 'burn-in' station to be tested at the tracker nominal working temperature in a cold room. Here a final check of the structure performances (component functionalities, module cooling, noise) before assembling the shells together is performed.
Then the half cylinders are coupled together and inserted one into the other to form the four layers TIB. Finally the TIB and TID are fixed together and the services are routed to a patch panel. The entire TIB-TID is composed by two of this macro structures, forward and backward, which are joined together directly inside the tracker support tube, which also hosts the TOB and the two TECs, to complete the CMS Silicon strip tracker.

7 Conclusions

In order to fully exploit the collider physics potential the CMS Silicon Strip Tracker has been design to perform tracking and vertexing at the LHC at any luminosity up to $10^{34} cm^{-2} s^{-1}$. The detector modules, which are the project most critical component, have been produced with an average yield of 96%. The integration of the various elements to form the tracker sub-detectors is about to be completed. The next and final step will be the assembly of the whole tracker in its support tube and the commissioning of this scientific apparatus to prepare it to take data at the LHC.

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