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TESTING THE READOUT ELECTRONICS OF THE CMS TRACKER MODULES WITH LT SETUP

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The tracker part of the CMS detector will be built with ~16000 silicon detector modules and kept at –10 °C during the ten years' operation of the LHC. All the materials of the modules have to be verified to have a good performance at this low temperature before their installation into the CMS Tracker. In order to track their performance quality assurance tests are done with two different systems. Of the two setups used, the module LT system is the one to identify whether the performance of readout electronics and leakage current flowing on the silicon sensors are affected by low temperature or not. In this paper the detailed layout of the CMS TOB modules, their front-end hybrids are given. In addition to that, LT testing results of 190 TOB modules that were produced and tested in 2004 by FNAL–CMS group are given.

Камера CMS-детектора будет собрана из ~16000 кремниевых детектирующих модулей и будет работать при –10 °C в течение десяти лет на LHC. Все материалы модулей должны быть протестированы при этой температуре перед установкой их в камеру CMS. Чтобы проверить их функционирование, для гарантии проводятся тесты с двумя различными системами. При этом модуль LT-системы используется для того, чтобы установить, влияет или нет низкая температура на работу считывающей электроники и ток утечки, попадающий на кремниевые детекторы. В этой статье описано детальное расположение модулей CMS TOB и их смешанные конструкции. В дополнение даны результаты LT-тестирования 190 TOB-модулей, сделанных и проверенных в 2004 г. группой FNAL–CMS.

INTRODUCTION

The CMS (Compact Muon Solenoid) experiment will observe pp collisions at 14 TeV center-of-mass energy with a luminosity of 10^{34} cm$^{-2}\cdot$s^{-1}. The bunch crossing frequency will be 1/25 ns = 40 MHz and the expected minimum bias events per bunch crossing are ~ 20. This will result in ~ 2000 charged particles tracks per event. A momentum resolution of ~ 1–2% P_T at 100 GeV/c and an impact parameter resolution of ~ 10–20 μm is required from the tracker. The tracker part of the CMS detector will be equipped with two different silicon technologies. While the innermost part will consist of silicon pixel detectors, the silicon microstrip tracker (SMT) part will be composed of silicon microstrip detectors and it will be assembled in four subdetectors: the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Outer Barrel (TOB) and Tracker End Caps (TEC). The total area of

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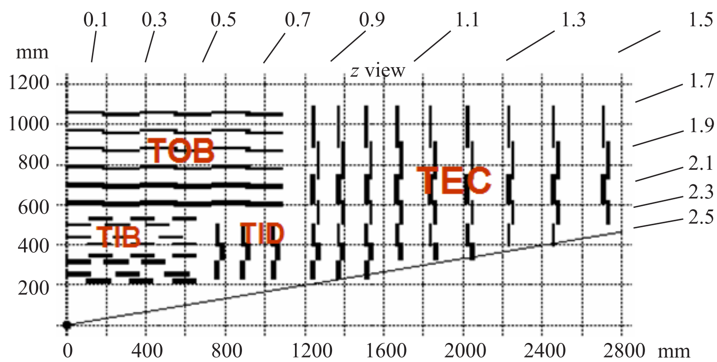

Fig. 1. A quarter view of CMS SST. Locations of the subtrackers and number of layers are seen from the figure. Thin and thick lines represent the single- and double-sided modules, respectively. Top axis belongs to pseudorapidity

the CMS tracker is about 216 m^2 and $\sim$16000 silicon detector modules will construct this area. Figure 1 shows the R–z view of the SMT. TIB and TOB volumes will be instrumented with 10 cylindrical layers, whereas the TID and TEC are composed of 12 disk layers on each end of the detector. A detailed description of the CMS Tracker can be found in Refs. [1, 2].

1. SILICON MODULES

SMT detectors are standard p^+-on-n microstrip detectors with AC readout and polysilicon bias resistor. The usage of a low-resistant bulk ($\sim$1.5–8 k$\Omega \cdot$cm) provides the sensor to be depleted at a manageable voltage over the entire LHC (Large Hadron Collider) run time. Crystallic lattice orientation of the silicon is $\langle 100 \rangle$. A detailed description of CMS silicon sensors can be found in Ref. [3]. A schematic view of the CMS silicon sensor is seen in Fig. 2.

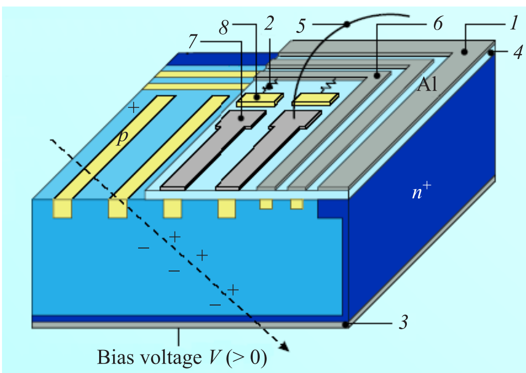

Fig. 2. The CMS silicon strip sensor [4]: *1* — guard ring (ground); *2* — bias resistor (poly); *3* — Al backplane; *4* — SiO_2 layer; *5* — bond wire; *6* — bias ring; *7* — AC pad; *8* — DC pad

These silicon sensors are organized in the modules. Modules have different geometries in order to cover all the volume of the tracker and optimize detector spatial resolution. Inner barrel modules are built with thin sensors to minimize channel occupancy and channel count. TIB, TID and four of the TEC layers will be constructed with 320 μm thin sensors, and only one sensor is used in the production of the modules of these layers. TOB layers and outer three layers of the TEC will be constructed with 500 μm thick sensors. Readout strips of the «barrel» and «disk» modules are organized along the z and radial directions, respectively, allowing the readout of $r\phi$ coordinates. They give 2D information of the tracks. In order to extract a space point the double-sided modules, back-to-back sandwich of $r\phi$ modules, and stereo modules with the strips tilted by a 100 mrad angle are used. Two innermost layers of TIB and TOB, the two innermost rings of TID and the TEC rings with $r \leqslant 40$ cm and with $60 \leqslant r \leqslant 76$ cm will be constructed with double-sided modules. This layout of STM will allow one to measure 8 to 14 points for high momentum tracks with $|\eta| < 2.5$. About half of these points are 3D points. All the modules consist of a carbon fiber frame, one or two silicon sensors, and a front-end hybrid.

APV25 chip is the main readout unit and each module houses four or six APVs on the front-end hybrid. The APV25 is a 128-channel analogue pipeline chip. It is manufactured by IBM in a 0.25 μm CMOS process to take advantage of the radiation tolerance, lower noise and power, and high circuit density which can be achieved [5]. APV25 chip has two operating modes: peak and deconvolution modes. In addition to APV25 chip, there are ASICs (APVMUX, PLL and DCU) and pitch adapter on the front-end hybrid.

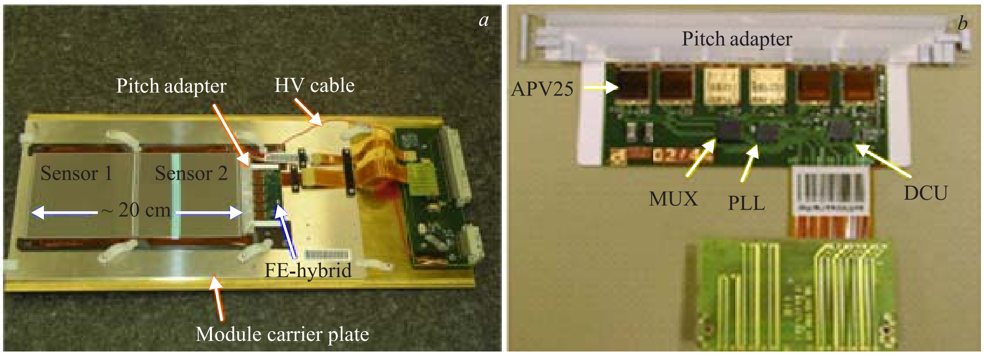

Fig. 3. CMS TOB silicon detector module (*a*) and close view of the front-end hybrid (*b*)

Modules to be described in this paper are CMS TOB modules. CMS TOB modules consist of two $\sim 10 \times 10$ silicon sensors. As we mentioned earlier, the thickness of these sensors is about 500 μm. Some of TOB modules will have four APV25 chips, while the rest will be with six APV25 chips. Figure 3 shows the size of these modules and the location of the subunits.

2. QUALITY ASSURANCE TESTS OF THE CMS TRACKER MODULES

During the production and testing period many problems can arise from transportation, assembly failures and handling the components. When assembled, the modules have to be verified to provide the physics requirements of the CMS experiment. For this purpose different test centers were organized by the CMS Tracker collaboration. Module production and qualification efforts are still in progress in these testing centers. After the vendor verification of the silicon sensors and FE hybrids all the components are sent to these centers to assemble the modules. For the testing mission two different test setups are used in these centers: ARC (APV Readout Controller) and LT (Long Term) (see Fig. 4). The former is a fast-testing setup and allows us to quickly identify and possibly correct module problems. The latter is very complex to operate but results taken with it have very useful information. It thermocycles the modules between the temperatures $+20$ and -20 °C and presents the effect of low temperature on the module readout units and sensors. LT system uses a prototype of CMS DAQ (Data AcQuisition) system. Meanwhile, in the running of this system environmental conditions can be managed by the tester. Since all module failures affect the analogue data readout from the strip we need to understand the influences of the low temperature on the modules. So this is the system that we can convince ourselves.

Fig. 4. ARC (*a*) and LT (*b*) systems for module testing

Fermi National Accelerator Laboratory (FNAL)'s SiDet (Silicon Detector Center) is one of these production and testing centers. It is responsible for assembling and testing all of the CMS TOB modules. In the following steps we are going to explain which electrical parameters and measurements are performed to grade a module as good or bad. We will do that by evaluating 190 CMS TOB modules. The results we will give were taken with LT system at FNAL. We are going to conclude their performances using CMS TOB community's bad channel selection criteria.

3. FAILURES AFFECTING MODULE PERFORMANCE

The basic types of faults that are identified during module testing include pinholes, one sensor unbonded (sensor–sensor open), two sensors unbonded (sensor–PA open), shorts, and high noise. These are the most essential fault types that play a central role in the performance of the modules.

Pinholes. Pinholes are the shorts or ohmic connections between the aluminum strips and the corresponding $p+$ implants of channels in the sensor. They are the most dangerous type of failures since the flow of a leakage current in the APV can cause the whole readout chip to be dead.

Short and Open Channels. Shorts are the electrical connections of two channels in the pitch adapter, wire bonds or sensors. Opens are breaks in the pitch adapter traces, missing wire bonds between the pitch adaptor and a sensor or between two sensors, breaks in the aluminum strip in the sensors, and broken APV channels.

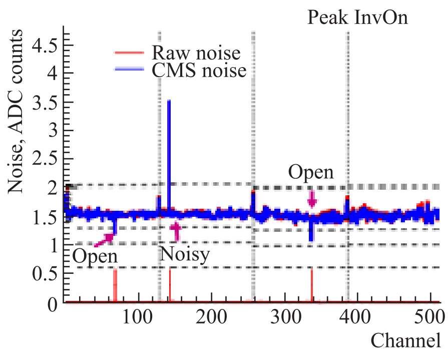

Fig. 5. Bad channels identified by LT test in the noise analysis

Identification of the above faults are done on the basis of the noise in the strips. Noise of a channel is given by

$$\sigma_i = \sqrt{\langle(\nu_i - \mathrm{ped}_i)^2\rangle} = \sqrt{\langle\nu_i^2\rangle - \langle\nu_i\rangle^2}, \qquad (1)$$

where ν_i is the digitized charge; ped_i is the pedestal for a given channel i. Based on the results of the tests, modules are graded due to the number of faulty channels and leakage current as determined by the LT test. Grade A is assigned to modules with less than 1% bad channels, and grade B is assigned to modules with 1–2% of bad channels. Modules failing these requirements are graded as C or F in accord with the module grading specifications. In Fig. 5 bad channels identified in the noise test are seen.

4. PERFORMED MEASUREMENTS IN THE QUALIFICATION PROCESS

IV Measurements. IV measurement of the silicon sensors is made to identify channels with high leakage currents. It is done for the bias voltage growing in the range from 0 to 450 V with the raising steps of 50 V. The IV curves are interpreted in terms of leakage current. A module drawing a maximum leakage current, 20 μA for TOB modules, before reaching the 450 V is graded as bad.

Pedestal and Noise Measurements. The pedestal data is used for data correction and noise calculation purposes. The noise measurements are sensitive to all typical hybrid and module failures. They are also sensitive to environmental conditions such as grounding and ambient noise sources. From these tests we can identify noisy channels, pinholes and open candidates.

Calibration Pulse Shape Test. Through this test, functioning of the internal calibration circuit and observation of strip faults such as opens, pinholes and shorts are investigated.

Modules are analyzed on the basis of the bad channel cuts. It is a strategy to eliminate any really bad channel. A channel failing any of the cuts in any mode is marked as «bad». Channels with a noise higher (lower) than the cut value will be tagged as noisy (open). Cut values determined for CMS TOB modules are summarized in Table 1.

Table 1. **Cut values for bad channel identification of CMS TOB modules**

Test	Cut values		Fault ID
	Peak mode	Dec mode	
Noise run	$N < 0.6$ ADC 0.6 ADC $< N < 1$ ADC 1 ADC $< N < 1.3$ ADC $N > 2.0$ ADC	$N < 0.95$ ADC 0.95 ADC $< N < 1.4$ ADC 1.4 ADC $< N < 1.7$ ADC $N > 2.4$ ADC	Pinhole One sensor open Two sensors open Noisy
Pulse shape	$\|PS/\langle PS\rangle\| < 0.85$ ADC $\|PS/\langle PS\rangle\| > 1.15$ ADC	$\|PS/\langle PS\rangle\| < 0.8$ ADC $\|PS/\langle PS\rangle\| > 1.12$ ADC	Low pulse height High pulse height
Peak time	$(PT - \langle PT\rangle) < -30$ ns $-30 < (PT - \langle PT\rangle) < -8$ ns $-8 < (PT - \langle PT\rangle) < -4$ ns $(PT - \langle PT\rangle) > 10$ ns	$(PT - \langle PT\rangle) < -30$ ns $-30 < (PT - \langle PT\rangle) < -4$ ns $-4 < (PT - \langle PT\rangle) < -2$ ns $(PT - \langle PT\rangle) > 10$ ns	Pinhole One sensor open Two sensors open Noisy
Pinhole	PH > 40 ADC	—	Pinhole
CMN	< 0.5 ADC	—	CMN noise

5. PERFORMANCE OF THE TOB MODULES

We have tested 151 «4-APV» modules and 39 «6-APV» modules, for a total of 107264 channels. In the process of LT testing, each time three records are taken. First record belongs to the data taken at $+20\,^{\circ}$C, while the one performed at $-20\,^{\circ}$C is for cold record. The last record belongs to the run that brings the LT system back to the $+20\,^{\circ}$C temperature. In the analysis of the last record it is intended to verify that no extra defects and damages are happening during thermal cycling of the modules. The most powerful way to see the

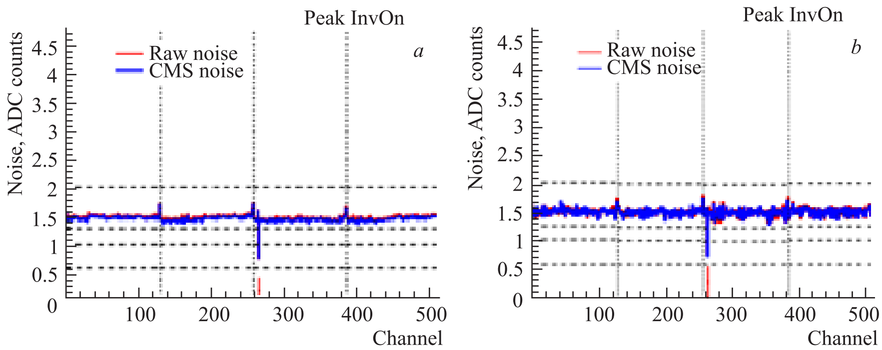

Fig. 6. Noise measurements from ARC (*a*) and LT (*b*) systems for a module

temperature effect on the modules is to compare noise measurements for ARC system and LT system. Testing procedure of these two systems is the same, except an additional factor of LT: temperature cycling. So the other parameters can also be handled in a similar way.

Table 2. **Module grading criteria**

Grade	Bad channels, %	Sensor leakage
A	$n < 1$	
A/F	$n < 1$	$I_{\text{leak}} > 5\ I_{\text{sensor}}$
B	$1 < n < 2$	
B/F	$1 < n < 2$	$I_{\text{leak}} > 5\ I_{\text{sensor}}$
C	$n > 2$	
C		$I_{\text{leak}} > I_{\max}$
F	$n > 2$	$I_{\text{leak}} > I_{\max}$

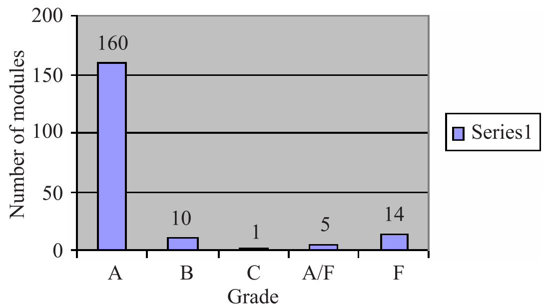

Fig. 7. Final grades assigned to tested modules

Figure 6 displays noise versus channel number for a module. Plot *a* is extracted from ARC test and plot *b* is extracted from the last record of LT test. The plots show consistency between two systems for the identification of the faulty channels in peak mode of the APV chip. In particular, the sensor–sensor opens are visible in the figures correspond to channels 265.

In Table 2 we see the grading criteria, and final grades assigned to 190 tested modules are shown in Fig. 7.

CONCLUSION

LT system is produced by CMS community in order to understand the behavior of the module electronic readout units and mechanical supports at low temperature. The LT system was very important to examine the behavior of the quality identifier criteria at low temperature. We were hopeful of improving the performance of the modules at low temperatures. All the modules were read out in a temperature scan, starting from $+20$ down to $-20\,^{\circ}$C and back to the $+20\ ^{\circ}$C. We saw that decrease in the temperature affected current consumption, data baseline increases for noise in deconvolution mode of APVs, and calibration pulse shapes change in the temperature cycles. Pedestal distributions stayed stable during different temperature cycles. The assembly and testing operations were very smooth and modules were largely in the mechanical grade A category. There were open questions for modules of grade F. These modules were taken under technical inspection. The module bonding operation did not lead to the formation of any new pinholes in over one hundred thousand bonds. There were some number of shorts and «burned» APV channels that were identified and dealt with, but these represent less than ten percent of the small number of vendor-identified pinholes and shorts.

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