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Module Production for the CMS Tracker: Problems and Achieved Quality

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Abstract

The construction of the CMS Inner Tracker is very close to be completed. The various components are being mounted on the large structures and by the end of 2006 the tracker assembly will be finished at CERN. The basic elements of the strip tracker are the silicon sensor modules. In total about 15000 modules of various geometries have been built by a large collaboration of institutes. This paper will explain the design and the semi automatic assembly procedures. The major problems which appeared during this production are discussed. The final section gives an overview of the obtained results.

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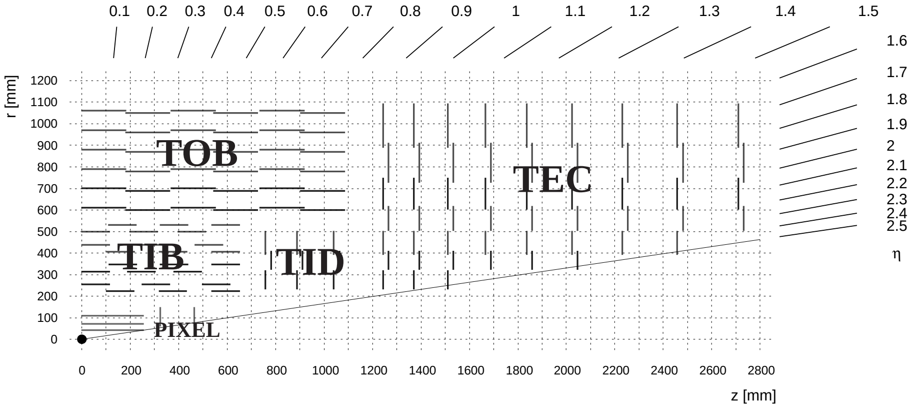

Figure 1: The CMS Inner Tracker Layout.

Table 1: Some key parameters from the silicon strip tracker construction.

Area of active silicon	$\approx 200\ m^2$
Number of silicon sensors	24,244
Different sensor designs	15
Number of modules	15,232
Mechanically different module designs	27
Number of strips	$\approx$ 9,600,000
Number of electronics channels	$\approx$ 9,600,000
Number of readout chips	$\approx$ 75,000
Number of wire bonds	$\approx$ 25,000,000

1 The Layout of the CMS Inner Tracker

At CERN, the European Laboratory for Particle Physics in Switzerland, the large hadron collider LHC is under construction. The LHC will produce proton-proton collisions at a centre of mass energy of 14 TeV, the startup of the LHC is foreseen for 2007. To exploit this machine the CMS experiment, a multipurpose experiment, is under construction at CERN to take data at the startup of the LHC.

The CMS detector will consist of several shells of different detector elements. Particles created in the high energy collisions in the very center of the detector will first traverse the ‘Inner Tracker’ a system of silicon sensors designed to detect charged particles.

This Inner Tracker [1] is divided into substructures: The pixel detector very close to the interaction point and the strip tracker consisting of the inner barrel detector (TIB), the inner discs (TID), the outer barrel (TOB) and the two end cap detector systems (TEC). The overall length of the Inner Tracker is 5.4 m with a diameter of 2.4 m. The temperature inside the tracker will be adjusted such that the maximum temperature of the silicon sensors will not exceed -10^oC.

A quarter of a cut through the Inner Tracker is shown in figure 1. The solid lines in this sketch represent the silicon sensor modules. The modules of the TIB are mounted on four and the TOB modules on six concentric shells. The supporting structures for the TID and TEC are discs, two times three discs for the TID and two times nine discs for the TEC.

Table 1 lists some numbers illustrating the overall dimension of the Inner Tracker strip detector.

2 Module Design

The basic construction element of the silicon strip tracker is a module (see figure 2). The supporting frame of a module is made of carbon fiber or graphite. Glued onto the frame is a Kapton layer to isolate the frame from the silicon and to provide the electrical connection to the silicon backplane. A Kapton multilayer hybrid laminated to a ceramic support holds the readout chips and the auxiliary chips. A glass pitch adapter is mounted between the hybrid and the silicon sensor to match the different pitches of the chips input pads and the sensor strips. The electrical connections are made by wire bonds between the individual channels of the readout chips and the lines on the pitch adapter, between the pitch adapter and the first sensor, and in case of a two sensor module between

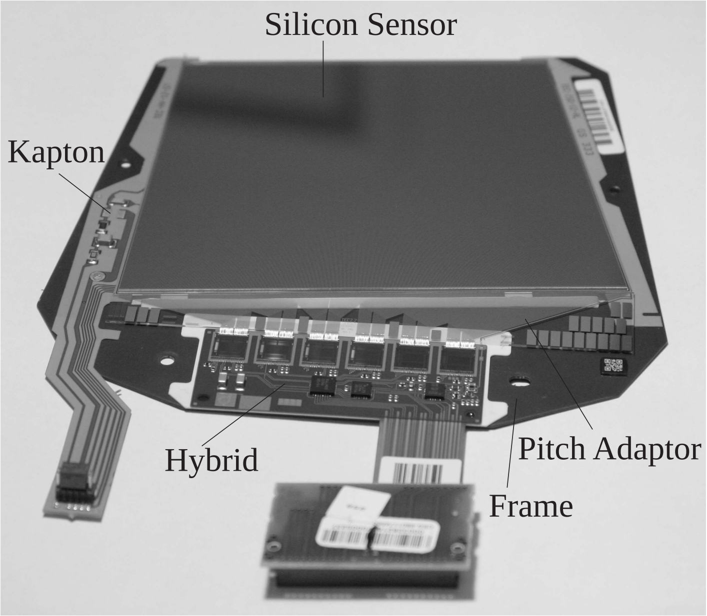

Figure 2: A ring 2 module for the TEC.

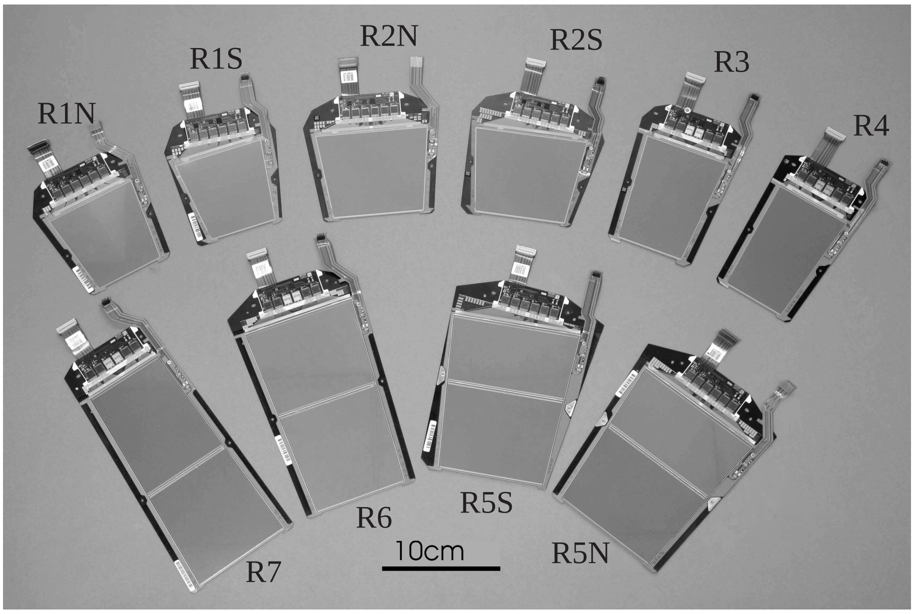

Figure 3: The ten mechanically different modules needed for the TEC.

the two sensors. The TIB, the TID and the four inner rings of the TEC consist of modules with only one silicon sensor, whereas the modules of the TOB and the three outer rings of TEC hold two sensors.

All barrel modules are rectangular. The modules on the discs for TID and TEC have a wedge shape in order to form rings and thus allowing a precise measurement of the z and phi coordinates. Figure 2 shows a module for the second ring of the TEC. The first two layers in TIB and TOB, the first two rings in TID and the rings 1, 2, and 5 in TEC are instrumented with so-called double-sided modules. These are made of two independent single-sided modules, mounted back to back and rotated by 100 mrad with respect to each other.

Figure 3 shows as example the ten different module geometries needed to build the seven rings of the tracker end caps (R1-R7). The inner rings 1 to 4 consist of modules with one sensor (top row), while the modules for rings 5 to 7 consist of two sensors (bottom row). Ring 1, 2 and 5 modules exist also in a second geometry with tilted sensors for the second plane in double sided layers (R1S, R2S, R5S).

3 Module Production

3.1 Assembly

The assembly of the modules was done in so-called gantry centers at the following CMS institutes: Bari, Brussel, FNAL, Lyon, Perugia, Santa Barbara and Vienna.

These centers received the hybrids glued to the pitch adapter and already bonded, the frames holding the isolating Kapton and the silicon sensors. These components are assembled using a computer controlled positioning system. This system is a commercially available unit (Aerotech AGS 10,000 gantry positioning system) modified for our needs. For each mechanically different module type a dedicated assembly platform had to be constructed. These platforms allow the assembly of 3 respectively 4 modules in parallel. During the assembly procedure pick up tools place the components, a glue dispensing system applies the different glues used. High geometric precision is achieved using a CCD camera with pattern recognition. The nominal placement accuracy is 5 μm. The following three glue types were used for the assembly:

- Components to frame, except sensors: Huntsman - 2011 ARALDITE
- Sensors to frame: Dow Corning - 3140 RTV (Silicon Rubber)
- Conductive connection Kapton to sensor backplane: Polytec - EPO-TEK EE129-4

Further details on the gantry procedures can be found in [2].

3.2 Bonding and Tests

The hybrid and pitch adapter assemblies were bonded and tested at CERN and FNAL. The other bonding connections on the modules and the subsequent functional tests were done at the following CMS institutes: Aachen, Bari, Catania, Firenze, FNAL, Hamburg, Karlsruhe, Padova, Pisa, Strasbourg, Torino, Santa Barbara, Vienna and Zürich. Standard commercial bonding stations from different vendors were used by the bonding centers. The chosen wire type was aluminum with 1% silicon, medium hardness with a wire thickness of 25 μm.

After bonding a standardized test was performed to determine the electrical parameters. Details of this test setup, called ARC-system, are explained in reference [3].

4 Major Problems during the Production

4.1 Sensors

The majority of the CMS sensors [4] was delivered by Hamamatsu Photonics, Japan. A small fraction was delivered by STMicroelectronics, Italy. The various problems encountered during the procurement of these sensors are already described in [5] and [6].

4.2 Hybrids

During the production of the multilayer hybrids a major problem appeared. Long time tests of modules, including thermal cycles, revealed electrical failures of the hybrids. The subsequent investigation showed that vias between different layers of the hybrids systematically broke. These failures forced a complete stop of the production and a redesign of the hybrids. To improve the design the hole diameter of the vias was increased from originally 100 μm to 120 μm. More important however was an introduction of an additional central Kapton layer to reduce the thickness of the glue between the layers. These design changes together with additional quality tests at the company finally solved the problem.

4.3 Conductive glue

In the original design of the TOB and TEC modules the contact between the copper lines on the Kapton, carrying the bias voltage, and the backplane of the sensors was realized by a few dots of conductive glue. Figure 4 shows such glue spots on the Kapton of a disassembled module. Long time tests including thermal cycles revealed an increase of the resistance of this connection on a high percentage of modules and occasionally a complete failure

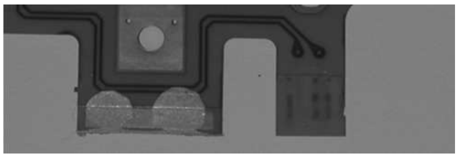

Figure 4: Glue spots applied in the original design. To show the glue spots the Kapton was detached from the silicon.

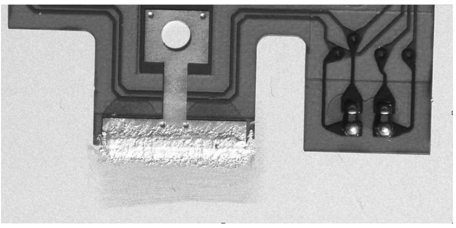

Figure 5: Glue applied following the ”glue enhancement procedure”.

of this connection. The problem was attributed to an isolating aluminum oxide layer on the sensor backplane which was not efficiently broken during the automatic assembly procedure. This conclusion was confirmed by experts from the company supplying the glue. The problem was discovered during the period of high throughput production and hence a fast solution had to be developed. The TEC consortium introduced as a first step a so-called ”glue enhancement procedure”. In this procedure the surface of the backplane was brushed prior to the application of the glue, thereby removing the oxide. In addition a much larger glue dot was applied (see figure 5) to increase the surface. Measurements suggested furthermore that the application tool should be used to stir the glue during the application of the glue.

Many tests on modules with such an enhanced glue connection were performed and no further failures were observed. Nevertheless, for safety reasons it was further decided to bond the backplane connection. In the final CMS tracker all TOB modules and almost all TEC modules have a bonded backplane connection. Only about 355 TEC modules remain glue enhanced without bonds. The TIB and TID modules were already wire bonded in the original design.

5 Overview of the Results from the Module Production

The achievements of the CMS module production are summarized in Table 2. In the column of bad modules the modules outside the mechanical and electrical specifications are counted. The numbers presented in this table take also into account modules damaged during the mounting procedure and the still ongoing repair effort to recover these.

The total number of modules needed to complete the tracker is 15232. Therefore about 4.5% good spare modules have been produced.

5.1 Results on the example of the TEC modules

In this chapter an overview of the results obtained during the production of the TEC modules is given. The production of the TEC modules is selected to give a representative overview of the achieved module quality: They comprise almost half of the total number of modules and, during the final period of the production almost all institutes listed in chapter 3 were involved.

	Modules produced	Good	Bad	Yield
TIB/TID modules	3945	3810	135	97%
TOB modules	5434	5348	86	98%
TEC modules	7228	6761	467	94%
Total	16607	15919	688	96%

Table 2: Overview of the CMS module production (Status September 4, 2006).

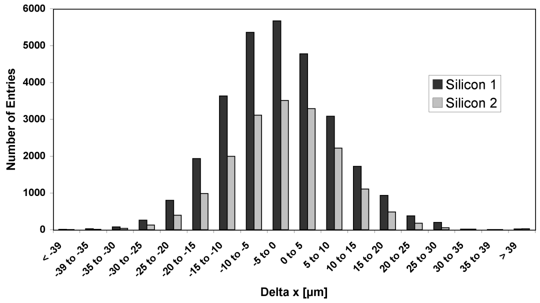

Figure 6: Deviation from the sensor's nominal position in the x coordinate. The specification requires less than 39 μm.

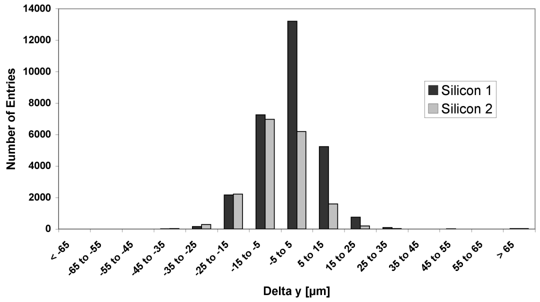

Figure 7: Deviation from the sensor's nominal position in the y coordinate. The specification requires less than 65 μm.

The results are discussed in the logical order of the production. The first parameter of interest is the achieved mechanical precision. Figure 6 shows the deviation from the nominal position of the first and second silicon sensor with respect to the module's frame in the x coordinate. The x coordinate is perpendicular to the strips of the sensors. Figure 7 shows the corresponding plot for the deviation in the y coordinate parallel to the strips. The rotational deviation from the nominal position for the first and for the second silicon sensor with respect to the module's frame and the angle between the two silicon sensors is presented in figure 8.

The assembly of the modules with the semi automatic gantry systems resulted in only a few modules outside the mechanical specifications. For the whole TEC production this was only the case for 36 modules (0.5%).

Concerning the quality of the wire bond connections the specification for the mean value of the bond pull strength, calculated over one module, was defined to be at least 6 g. Clearly, these pull tests could only be done on a sample bases. In the beginning of the production every 50th bond wire was pulled and subsequently remade. The sample size was reduced as the production went on. As illustrated in figure 9 the measured values exceeded well the specification for both the bonds between the pitch adapter and the sensor as well as between the two sensors. Only 2 TEC modules (0.03%) had to be rejected due to weak bonds.

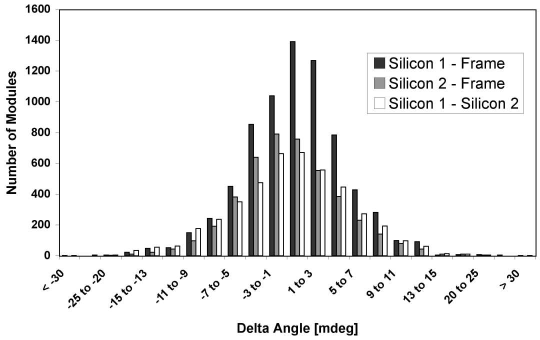

Figure 8: Angular deviation of the silicon sensors. The specification requires less than 30 mdeg for the angle "silicon to frame" and 20 mdeg for the angle between the two silicon sensors.

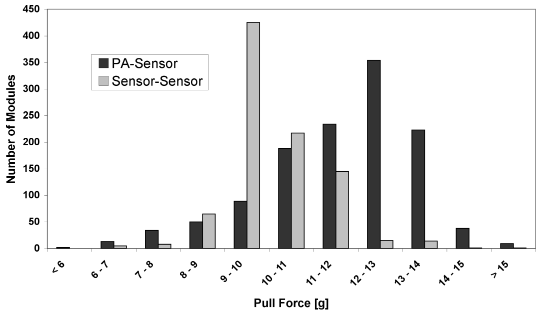

Figure 9: Bond pull strength. Each value represents the average of the measurements on one module.

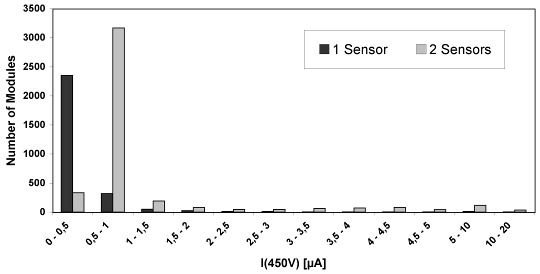

Figure 10: Module leakage current measured at 450 V bias voltage. The specification requires less than 10 μA for single sensor modules and 20 μA for double sensor modules.

The final tests before a module is declared qualified for CMS are several electrical measurements. Figure 10 shows measured current values of production modules at a bias voltage of 450 V. In perfect modules this current reflects the sum of the leakage currents of the assembled sensors. To be used for module production every sensor was tested before assembly and only accepted if the leakage current was below 10 μA. In reality most of the sensors had much lower currents (see [5]). Consequently the maximum current allowed for modules is 10 μA for single sensor modules and 20 μA for two sensor modules. As seen in figure 10 the majority of the modules had currents of less than 0.5 μA or 1 μA for single and two sensor modules respectively. Note that the plot contains only modules passing the specifications, modules which failed due to high currents or breakdown at voltages below 450 V are not shown.

In figure 11 the number of faulty strips separated for modules with 512 strips (4 APV readout chips) and for modules with 768 strips (6 APV readout chips) is presented. The counting of bad strips comprises all reasons a strip does not perform as required. These are noisy strips, strips with shorts between the p+ implant and the readout aluminum lines (pinholes), shorts between the aluminum lines on the sensors or on the pitch adapter, broken aluminum lines, broken bonds and non-functioning APV channels. The specification to accept a module requires less than 2% of faulty channels. On average the TEC modules have only 0.16% faulty channels.

5.2 Analysis of TEC module failures

A breakdown of the reasons for module failures for the completed TEC production is shown in figure 12. The largest fraction are modules with too high leakage currents - so-called IV failures (108 modules). As all sensors

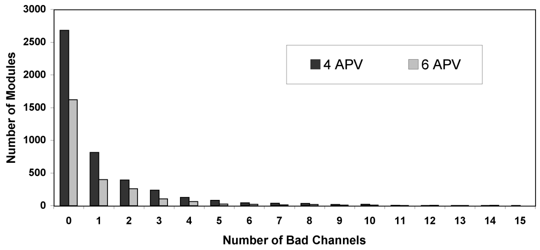

Figure 11: Number of bad strips per module determined at 450 V bias voltage. The specification requires less than 2%: less than 11 (16) channels for modules with 512 (768) strips.

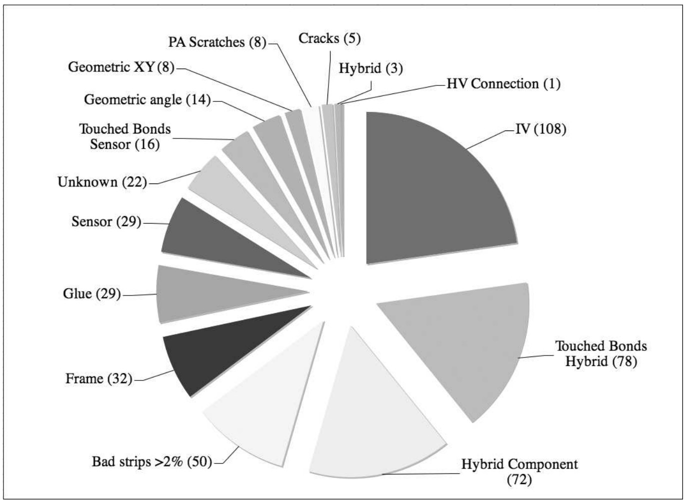

Figure 12: Breakdown of the reasons for failures of TEC production modules. In brackets are the number of modules showing the specified failure.

were tested prior to module assembly this clearly points to mishandling during the production or at module mounting. The second largest fraction are ”touched bonds” on the hybrid (78 modules) - again a handling issue. The fraction of ”touched bonds” on the sensor to pitch adaptor connection is much lower (16 modules) because these damages could be repaired in many cases. The third largest fraction are component failures on the hybrid (72 modules). Finally, for the rest of the rejected modules other types of failures are responsible.

6 Summary

The module production of the CMS tracker collaboration has been completed. More than 16600 modules have been built with a yield of about 96%. The number of reserve modules is sufficient to safely finish the CMS tracker construction. The modules exhibit an excellent quality. From the 9.6 million individual channels of the silicon strip tracker only 0.1% to 0.2% are not working according to specifications and are therefore marked as faulty.

Acknowledgments

The CMS Inner Tracker module production was an effort of a large number of colleagues in the CMS gantry and bonding centers over a period of several years. I would like to acknowledge their effort and dedication to complete the CMS tracker. Special thanks goes to Stefan Hänsel for preparing the plots for this paper.

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