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The CMS Silicon Strip Tracker: Design and Production Status

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Abstract

The CMS Silicon Strip Tracker (SST) will be equipped with 15000 silicon micro-strip detector modules covering a surface of 200 m². This paper details the SST layout and updates the status of construction. Progress in the fabrication of module components is detailed, with focus on the front-end hybrid and silicon sensor production. The assembly of over 2200 modules using industrial methods is described; the quality assurance protocols have resulted in modules of extremely high mechanical and electrical quality.

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1 Silicon Strip Tracker Overview

The CMS Silicon Strip Tracker (SST) will consist of about 15,000 detector modules assembled in four discrete sub-detectors: the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Outer Barrel (TOB), and the Tracker End Caps (TEC). Figure 1 shows a R-z quadrant of the SST. The TIB and TOB cover the central region of the experiment and consist of 10 layers of silicon micro-strip detectors in a cylindrical, barrel geometry. The TID and TEC cover the forward regions of the experiment and consist of 12 layers of disks on each end of the detector. For a more detailed description of the CMS Silicon Strip Tracker see refs. [1, 2].

Figure 1: Schematic of one R-z quadrant of the SST, showing the location of the TIB, TID, TEC, and TOB. The horizontal and vertical axes are in mm; the top axis is in pseudorapidity. The thin (red) lines represent single-sided layers; the thick (blue) lines represent layers with modules mounted back-to-back for three dimensional space measurements.

1.1 Modules

The fundamental active element of the SST is a module. Each module is made up of a carbon fiber support structure, a front end hybrid circuit, and one or two single-sided silicon sensors. The majority of modules are aligned along the z-axis in the barrels and radially in the disks to provide R- ϕ and z- ϕ information, respectively. In order to provide three dimensional track information for tracking and vertexing, some modules are built with a stereo angle of 100 mrad. Standard and stereo modules are then assembled back-to-back in order to provide the three dimensional space point.

The modules have differing sensor geometries in order to optimize detector spatial resolution, and to minimize channel occupancy and channel count. The inner layers of the SST (TIB, TID, and the inner 4 layers of the TEC) use 320 μm thick sensors with a pitch of 80–120 μm and a length of ~ 10 cm. Only one sensor is used in each module in order to minimize the channel occupancy. The outer layers of the SST (TOB and the outer 3 layers of the TEC) use modules with two silicon sensors with a wider 120–200 μm pitch, as the detector occupancy decreases with radius. 500 μm thick sensors are used in order to increase the signal to compensate for the increased noise due to the increased strip length (load capacitance).

1.2 Front-end Hybrids

The front-end hybrid provides filtering, and distributes power and control lines for the various ASICs used for signal readout and monitoring. Each front-end hybrid houses chips for amplifying and buffering the data (APV) [3], multiplexing data lines (MUX) [4], decoding the trigger and clock signals (PLL) [5], and monitoring the temperature, currents, and voltages of the module (DCU) [6]. After an extensive R&D program [7], the kapton flex circuit technology produced by Cicorel was chosen for the final hybrid. The flex circuit is laminated onto a ceramic substrate to provide a cooling path. The hybrids are stuffed and wire bonded at Hybrid SA.

Initially, fragility problems were encountered with the flex hybrids. First, the nickelized copper traces near the hybrid connector were shown to break with handling. Next in some batches, the power vias of the hybrids were shown to open during production and after use. Pictures of both problems are shown in figure 2. In both cases, the problems were recognized, diagnosed, and removed quickly due to the great relationship between the SST collaboration and the vendors.

Figure 2: Top: Cross-section of a broken hybrid power via. Bottom: Picture of a break in the nickelized copper traces near the hybrid connector.

1.3 Silicon Sensors

All CMS silicon sensors, designed based on the results of an extensive R&D program [8], use p^+ -on-n implantation. The final design uses a simple guard ring and strip geometry. The Aluminum coupling strips are wider than the p^+ implants, moving the high field region near the implant from the bulk silicon into the SiO_2 . Thus, the metal-overhang increases the breakdown voltage of the device. The design also utilizes $< 100 >$ silicon crystals which minimize the effects of surface damage after irradiation.

The thin $320\ \mu\text{m}$ sensors are produced by Hamamatsu Photonics (HPK). The sensors have been of exceptional quality with over a 99% acceptance in internal testing. Over 97% of the sensors have been delivered to CMS. Recently, a fraction of the thick $500\ \mu\text{m}$ sensor production have been moved to HPK in order to meet the production schedule. The first prototypes of each sensor type are to be delivered in June, and the first large batch of sensors to be delivered in July.

SGS Thompson Microelectronics (STM) produces thick $500\text{ }\mu\text{m}$ sensors for CMS. The STM production line has had historically higher rejection rate in internal testing of $\sim 10\%$. The high rejection rate would require full acceptance testing of all sensors, which would not be possible with the resources of the CMS sensor group. Recently, the first group of sensors with the finalized processing and quality control has been delivered to CMS. Due to the hard work of the CMS sensor group and STM, the internal yield of this batch has increased to over 98%. If the initial results of the acceptance testing holds for the entire batch, STM will be fully qualified for full production.

2 Module Production and Quality Assurance

Component availability has delayed the beginning of large-scale module production worldwide. In order to meet the scheduled completion date of June 2005, the module construction schedule has been compressed from 2 years to $1-1\frac{1}{2}$ years depending on the subsystem.

The previously described hybrid and sensor problems have affected the production of thick sensor modules (TOB and the outer TEC) much more severely than the inner modules built with thin sensors. In order to meet the significantly compressed schedule, the production and quality assurance capacity within the collaboration has been vastly increased over the last year, which will be described in the following sections.

2.1 Module Assembly and Mechanical Quality

Modules are assembled using automated robotic “Gantry” systems built by Aerotech [9]. The gantry systems consist of a camera, which surveys the various components, a robotic arm which can hold vacuum pickup tools for placing sensors and hybrids, and syringes to precisely dispense silicone epoxies. Removable assembly plates hold components for 3 or 4 modules depending on module type. Pattern recognition software feeds-back information to the motors in the gantry arm to correct for any rotation or translation in the placement of the sensors or hybrids.

The module components are placed with a precision of $\sim 10\mu\text{m}$ for translations perpendicular to the strips and 5 mdeg for rotations in the plane of the sensor strips. Figure 3 shows the mechanical precision of the first 1700 modules produced. 97% of the modules meet the stringent selection requirements, with most failures lying just outside of the angular requirements. After ~ 10 modules are built on a given assembly plate position, individual plate corrections to the alignment can be made. After such alignment, none of the modules have failed the mechanical selection requirements. After the modules are assembled, the assembly plates are removed from the gantry and placed in storage with the components held in place with vacuum for an overnight glue cure.

Figure 3: Measurements of the placement of silicon sensors relative to their nominal positions to the carbon fiber frame. The vertical lines show the acceptance criteria. Top: The difference in angle along the detector strips (in mdeg). Bottom: The translation (in μm) perpendicular to the sensor strips.

Figure 4: Pictures of SST modules. Left: a TIB module. Center: a Ring 6 TEC module. Right: a TOB stereo module.

To meet the new schedule, the assembly procedures have been optimized to increase through-put while keeping the high mechanical quality. Two person operation of the gantries where the next assembly plate is prepared while the current plate is being assembled, make the process highly efficient. In addition, the after glue-cure surveying of the modules has been moved to independent precision measurement machines which frees the gantries for production. These improvements have increased the demonstrated world-wide module assembly capacity to over 90 modules a day. At the time of the proceedings, more than 1150 TIB modules, 650 TEC modules, and 400 TOB modules have successfully been assembled. An example of TEC, TOB, and TIB modules are shown in figure 4.

2.2 Module Wire Bonding

Assembled modules are sent to 1 of 14 bonding centers in order to make the micro-wire bonds between the readout electronics and the silicon sensors. All centers are fully equipped and operational, using mostly Delvotec and Kulicke & Soffa wire bonders. The bonding capability easily matches the production capabilities of the gantry centers. The group has the ability to place over 130,000 bonds per day, which is the equivalent number of bonds as the entire CDF Run II silicon upgrade in two weeks.

2.3 Module Electrical Quality Assurance

The hybrids and modules are tested at all stages of module production in order to ensure that the performed operations do not introduce defects. To be used in the detector, the module must have less than 2% faulty channels. During the last year, much work has gone into the noise performance and shielding standardization of the test equipment. The current standard eliminates external noise sources, which has allowed for the development of a testing program which works for TIB, TEC, & TOB modules. In addition, results from different testing centers can now be combined for the same module type, reducing the time needed to find any systematic faults in the modules.

A more detailed description of the testing program can be found in ref. [10].

The fault finding algorithm is more than 99% efficient. The fault type and location was correctly identified in about 90% of the time. For those cases in which the fault type was not correctly determined, the different tests indicated different locations along the strip for open bonds. In all cases, the correct location of the open bond was found by visual inspection. In addition, less than 0.1% of good channels are flagged as faulty. In most cases, these channels are the edge channels of the APVs that are known to have a special noise and calibration injection behavior.

Prior to production, the goal was to produce modules with less than 1% faulty channels. As an indication of the high quality of the electrical modules components, the rate of faulty channels is 0.2% for single sensor modules and 0.55% for two sensor modules. The rate of introduction of faults during production is less than 0.1% for both single and two sensor modules. The historically low rate of faulty channels is made possible by the design of the modules which emphasizes robustness and simplicity.

3 Conclusions

The CMS Silicon Strip Tracker is currently under production. Many potentially serious problems in module components have been discovered and addressed. These setbacks have delayed the beginning of full-scale production significantly. In order to meet the delivery date, all of the production/testing procedures have been optimized, doubling our module production capacity. As of now, over 2200 modules have been produced using industrial methods with historically low rates of faulty channels. Full scale production of all subsystems will begin in the summer with module production finishing in the summer of 2005.

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