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The CMS Silicon Strip Tracker: System Tests and Test Beam Results

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Abstract

With a total area of 210 squaremeters and about 15000 single silicon modules the silicon strip tracker of the CMS experiment at the LHC will be the largest silicon strip detector ever built. While the performance of the individual mechanical and electronic components has already been tested extensively, their interplay in larger integrated substructures also has to be studied before mass production can be launched, in order to ensure the envisaged performance of the overall system. This is the main purpose of the system tests, during which hardware components as final as possible are being integrated into substructures of the tracker subsystems. System tests are currently being carried out for all subsystems of the tracker. In addition, silicon modules and electronic components have been operated and studied in a particle beam environment. In this report results from the CMS silicon tracker system tests and a test beam experiment at CERN are presented.

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1 The CMS Silicon Strip Tracker

The CMS silicon strip tracker is divided into four subsystems: the Tracker Inner Barrel and Inner Disks (TIB and TID), the Tracker Outer Barrel (TOB) and the Tracker End Caps (TEC). The modularity of the system can be seen in Fig. 1 where one quarter of the detector is shown in the longitudinal view. The total tracker will be cooled to an operating temperature of –10°C. A detailed description of the layout of the silicon strip tracker is available in Ref. [1] and references therein.

Silicon modules mounted within a radial distance of 60 cm from the beam line have 320 µm thick sensors, while the sensors of all outer modules have a thickness of 500 µm. Single- and double-sided modules are used, the latter being made of two single-sided modules mounted back-to-back with a stereo angle of 100 mrad. The sensor design is described in Ref. [2].

The TIB consists of four cylindrical layers. Each layer is constructed out of two carbon fiber (CF) half-shells per beam (z) direction. Strings carrying three thin modules are mounted inside and outside of the layer surfaces. The TOB is composed of six cylindrical layers. The basic structure of the TOB is a rod: a CF support frame, which carries either three double-sided (layers 1-2) or three single-sided (layers 3-6) thick modules on each side. Finally, each of the two endcaps of the TEC consists of nine CF disks. On each disk 16 petals, wedge shaped CF support plates which carry up to 28 modules arranged in seven radial rings, are mounted.

The readout is based on the APV25 chip [3] built in radiation hard 0.25 µm CMOS technology. This 128 channels chip implements a charge-sensitive amplifier, a shaper and a 192 cells pipeline (3.2 µs long). Two operation modes can be chosen: in peak mode only one data sample is processed, while in deconvolution mode three consecutive samples are summed with weights. This leads to a much shorter pulse and thus to correct bunch crossing identification in the high luminosity phase of the LHC. The signals of two chips are multiplexed onto one data line and converted to optical ones in Analog Opto-Hybrids (AOHs) [4]. The data are then transmitted to the control room, where VMEbus readout boards called Front End Drivers [5] (FEDs) provide opto-electrical conversion, digitization and zero-suppression.

The monitoring and control is handled by Front End Controller (FEC) VMEbus cards, which communicate via a digital optical link [4] in a token ring protocol with dedicated Communication and Control Units (CCU25) [6] mounted on the string/rod/petal motherboards. These chips distribute the control signals to the addressed modules, while trigger and clock signals are propagated to Phase Locked Loop (PLL) chips on the front-end hybrids.

![Figure 1: The CMS silicon strip tracker. One quarter of the detector is shown in the longitudinal view. Each line represents a silicon module.](image)

2 Results from System Tests and the May 2003 Beam Test

System tests are currently being carried out for all subsystems of the tracker: for the TOB at CERN, for the TIB/TID in Florence and Pisa and for the TEC in Aachen and Lyon. Both electrical behaviour, with emphasis on the noise and signal-to-noise performance, and the cooling performance are being studied and the design is qualified or optimized, if necessary.

For the TIB and TEC the most complete system tests up to now have been realized in a test beam environment at CERN during May 2003. The X5 beam in the CERN West Area provided muons and/or pions ($p = 120 \text{ GeV/c}$ for pions). The beam had a LHC-like time structure, with about 3 nsec long particle bunches, spaced by 25 nsec time periods.

The main difference between test beam and system test setups and the final CMS readout and control chains is that
Figure 2: Signal-to-noise distributions as measured in the TEC beam test, (a) for a ring four module (thin sensor, blank histogram) and a ring five module (thick sensors, filled histogram) at 0°C; (b) for the ring five module at 0°C (filled histogram) and room temperature (blank histogram). All runs were taken in peak mode.

Currently PCI mezzanine cards (PMC) are used for readout and control (PMCFED\[7\] and PMCFEC) instead of the final VMEbus cards. These PMC have no implementation of optical conversion, thus additional opto-electrical converters are necessary.

In the following the setups of the TEC and TIB beam tests and the TOB laboratory system test, along with first preliminary results, are described.

2.1 Test Beam Data Acquisition

In the test beam the most recent DAQ software, based on the XDAQ\[8\] framework, was used. For the first time, a prototype of the final run control\[9\] was available, and an online monitoring programme provided immediate feedback on the performance. For each subsystem (TIB, TOB, TEC) optical transmission of data as well as timing and control signals between the control room and the beam area was realized. Each subsystem used one PC with a PMCFEC and a second PC housing two or three PMCFEDs and a Trigger Sequencer Card, which distributed the particle trigger and the clock from the TTC system\[10\] to the FEC and the FEDs.

The commissioning of the individual subsystems was finished within about two hours. This included the tuning of the optimal FED sampling point, the adjustment of the timing difference between individual channels due to their different positions in the trigger distribution path, the optimization of AOH parameters (adjustment of the laser diode gain and bias current, to be repeated for each temperature change) and finally trigger latency and PLL delay scans to find the physics signal (the sampling point which gives the highest signal to noise). Automatized procedures are implemented in the software for all these tasks. Mostly the TIB, TEC and TOB subsystems were read out independently of each other, but finally the TIB and TOB DAQ systems were merged and the two subdetectors read out coherently like a single detector after only a few hours of commissioning. This shows the scalability and commissioning capability of the DAQ software.

2.2 The Tracker End Cap Beam Test

For the first time a prototype of a TEC petal, equipped with nine modules (four thin single-sided modules on ring four, four thick single-sided modules on ring six, plus one thick double-sided module on ring five), was studied in a test beam. Twelve front-end hybrids plus AOHs were distributed on the remaining positions. The petal was cooled via its own cooling pipe system and was kept inside a thermally and electrically isolated passive cooling box, flushed with dry nitrogen. Temperature and humidity inside the box were monitored and an interlock on the low voltage was implemented. Floating power supplies (not of the final design) were used for low voltage and also for high voltage to bias the detectors. Both low and high voltages were transmitted to the petal via 45 m long cables of the final design.

The system showed excellent performance in terms of the signal-to-noise ratio (S/N). The S/N distributions of all modules have been studied in peak mode running for a bias voltage of 350 V and an operating temperature of 0°C. In Fig. 2 (a) two examples are shown: S/N Landau peaks of 27 and 39 are found for a thin and a thick module, respectively. In Fig. 2 (b) the S/N of the same thick (ring five) module is compared for running at 0°C and at room temperature, under otherwise identical conditions. The S/N is increased significantly when the module is operated at 0°C, compared to operation at room temperature, where a S/N of only 33.5 is measured.

Figure 3 shows the results of bias voltage scans. For a ring four module a plateau in S/N is reached for a voltage of 190 V. A double-sided ring five module consists of two single-sided modules, each with two daisy-chained wafers, mounted with a stereo angle. For the two sensors of one single-sided ring five module the plateau voltages are 264 V and 265 V. It was possible to distinguish between the two sensors since the stereo angle was exploited to
calculate the radial coordinate along the strip direction. In this way the clusters can be assigned to the individual sensors. The plateau voltage is higher than the depletion voltage, since charge collection is incomplete without significant overdepletion. High plateau voltages at the start ensure that after type inversion due to irradiation only moderate bias voltages must be applied to maintain full efficiency.

![Preliminary](image.png)

Figure 3: Signal-to-noise ratio versus the square root of the bias voltage for a TEC ring four module (dashed line) and a ring five module (solid lines, both sensors are shown).

2.3 The Tracker Inner Barrel Beam Test

The TIB test beam setup consisted of a part of a half-shell of layer three with four strings. Two of these strings were equipped with three single-sided thin modules each, while the CCU25 and the mother-cable were mounted for all four strings. The TIB setup was thermally stabilized at room temperature. Temperature and humidity were monitored and interfaced to an interlock system. Two different prototypes of the final control room power supplies (from CAEN and LABEN), supplying both low and high voltage, as well as a 125 m long low inductance power cable of the final design were studied for their noise behaviour, and exhibited excellent performance.

The noise of the system was found to be very low. The common mode subtracted noise of a typical TIB module is shown in Fig. 4(a). The mean common mode subtracted noise is only 0.97 ADC counts. In Fig. 4(b) the dependence of the number of noisy strips of one module on the bias voltage is shown. The number of noisy strips is very small and stable.

The signal pulse shape, measured with a muon beam, has been reconstructed in peak and deconvolution mode. While in peak mode a (slightly adjustable) peaking time of about 55 nsec is found, in deconvolution mode the pulse is much sharper and the peaking time is below 20 nsec. This is known to be achieved at the cost of a lower S/N. However, with a typical Landau peak of 18 (for 300 V bias voltage), the S/N in deconvolution mode is still sufficiently high. In peak mode a S/N of about 26 is measured.

![Mean: 0.9700 RMS: 0.7492E-01](image.png)

Figure 4: Noise measurements with a TIB module in the test beam: (a) common mode subtracted noise; (b) the bias voltage dependence of the number of noisy strips.

2.4 The Tracker Outer Barrel System Test

The system test of the TOB is in a very advanced state. The system test of a single-sided rod is finished and the design has been validated. Currently a double-sided rod equipped with twelve $r-\phi$ modules is under test at CERN, and a CMS Note summarizing the results is in preparation.

The noise performance of the rod was tested extensively. A comparison between a single module setup, consisting
of a bare module, and the rod setup equipped with the same module shows compatible noise and common mode both in peak and deconvolution mode.

To test the TOB modules with real particles, a cosmic test stand has been realized. With this setup a S/N of 26 is measured in deconvolution mode.

For faster measurements, important during the mass production phase, the modules are exposed to a $^{106}_{44}$Ru $\beta$-source, which provides electrons with a maximal energy of 3.5 MeV and a trigger rate of 500 Hz. For electrons, the S/N is typically 33 in peak mode and 21 in deconvolution mode (Fig. 5). The difference in S/N for cosmic muons and electrons is mainly due to the different mean path lengths in the silicon. The double-sided modules have been exploited to calculate the hit efficiency, which is found to be as high as 99.8%. First tracking and alignment studies at the overlap of two double-sided modules were already carried out.

Figure 5: Signal-to-noise ratio measured on a TOB module using a Ruthenium $\beta$-source, in peak mode (left) and deconvolution mode (right).

3 Conclusions

The system tests of the TEC, TIB and TOB subdetectors of the CMS silicon strip tracker are in an advanced state. Increasingly more complex substructures are being integrated and studied in laboratory system tests as well as in test beam experiments. Up to now the design has been proven to work very well, exhibiting low noise and excellent signal-to-noise ratio performance. In the TEC system test a full petal will be integrated until the end of the year, while for the TIB the next step is the integration of four full single-sided strings. Mass production of silicon strip modules has started, and the first fully equipped substructures will be installed on the disk and barrel structures in the first half of 2004.

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