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Lessons Learned During CMS Tracker End Cap Construction

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Abstract

With more than 15 000 silicon strip modules and a silicon area of about 200 square metres, the CMS silicon strip tracker will be the largest silicon strip tracker ever built. More than half of the volume is occupied by the two end caps, which comprise about 42 % of the silicon strip modules. Construction of the end caps is far advanced. In this article the experience from module production, integration of medium-sized substructures, so-called petals, and from the integration of the end caps themselves is summarized.

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1 The CMS Tracker End Caps

The CMS silicon strip tracker [1], comprising more than 15 000 silicon strip modules and a silicon area of about $200\,m^2$, will be the largest silicon strip tracker ever built. To avoid reverse annealing and to limit the leakage current in the harsh radiation environment expected at the LHC, the tracker will be operated at a temperature of below $-10°$C. A cross-section through one quarter of the tracker in the $R - z$ view[1)] is shown in Fig. 1. It is composed of four sub-detectors: the inner barrel (TIB) with four cylindrical layers of modules; the inner disks (TID), consisting of three disks per side; the outer barrel (TOB) with six cylindrical layers; and the two end caps (TECs), which are composed of nine disks each. The end caps occupy more than half of the tracker volume and carry about 42 % of all modules.

The TECs cover the pseudorapidity region between 0.9 and 2.5, with the disks located at distances between 1.2 m and 2.8 m from the interaction point. The end caps, called TEC+ and TEC$-$ according to their location in the z (beam) direction, feature a modular design. Up to 28 modules are mounted in seven radial rings on both sides of carbon fiber support structures called petals [2]. Eight petals are mounted on each side of a disk. These so-called front and back petals differ in geometry and the number of modules mounted. A technical drawing of one TEC is shown in Fig. 2.

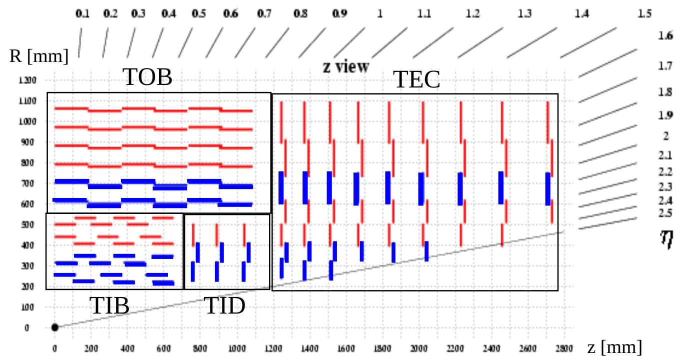

Figure 1: Cross-section through one quarter of the CMS silicon strip tracker in the $R-z$ view. Thin and thick lines represent single- and double-sided silicon strip modules, respectively. The individual subdetectors are labeled.

2 End Cap Module Production

The CMS silicon strip sensors are single-sided, AC-coupled p-on-n devices. Sensors with a nominal thickness of $320\,\mu m$ and a resistivity of 1.55-3.25 kΩ cm are used within a radial distance of less than 0.6 m to the beam axis because of their radiation hardness. Further outside, larger sensors with up to 20 cm long strips and a strip pitch of up to 200 μm are being used for reasons of cost and to limit the number of readout channels. To compensate for the increase in noise due to the increased sensor capacitance, sensors with a nominal thickness of $500\,\mu m$ are used in the outside region. One or two daisy-chained sensors are glued onto a carbon fiber/graphite support frame, together with the front-end hybrid and the Kapton strip that delivers the bias voltage.

In the TECs on rings 1, 2 and 5 double-sided modules are mounted. These are made of two single-sided modules that are mounted back-to-back with a stereo angle of 100 mrad, and provide information in both azimuthal (ϕ) and radial coordinates (thick module lines in Fig. 1).

Modules with 512 or 768 strips exist. The signals of the 512 or 768 silicon strips of a module are processed by four or six APV25 readout chips [3] that are mounted on the front-end hybrid. The APV25 is built in radiation hard 0.25 μm CMOS technology. It is a 128 channel chip which samples at a frequency of 40 MHz and implements a charge-sensitive amplifier, a shaper with a time constant of 50 ns and an analogue pipeline memory. After arrival of a first level trigger the signals are processed by an analogue circuit, for which two operation modes can be chosen: in peak mode only one data sample is used, while in deconvolution mode three consecutive data samples are reweighted and summed up [4], which leads to a much shorter pulse and thus to correct bunch crossing identification in the high luminosity running phase of the LHC. The analogue electrical signals are converted to optical signals in dedicated electro-optical converters, the Analog-Opto Hybrids.

[1)] In the CMS coordinate system the x-axis points towards the centre of the LHC ring, the y-axis points upwards and the z-axis completes the right-handed coordinate system. The azimuthal angle in the xy-plane is denoted as ϕ.

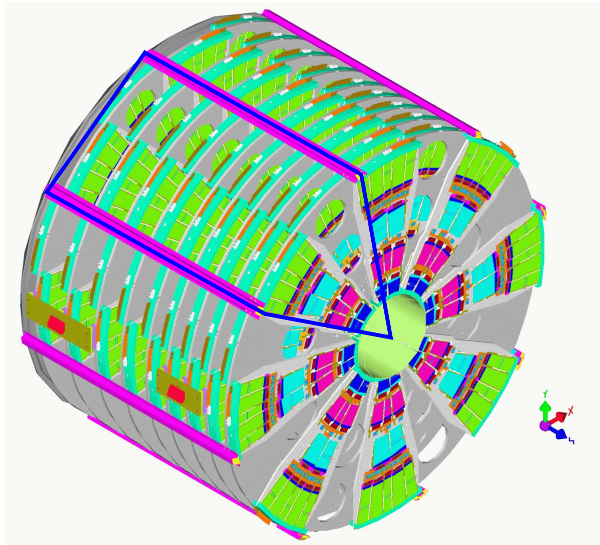

Figure 2: Technical drawing of one tracker end cap (TEC). The interaction point is located to the right. The eight front petals mounted on the front side of disk 1 are visible. The modules of rings 1, 3, 5 and 7 can be seen as well; the individual rings are shaded in different grey tones. The rings 2, 4 and 6 are mounted on the back side of the petals. One sector, corresponding to one eighth of a TEC in ϕ, is indicated.

Modules are assembled with precision pick-and-place robots, so-called gantries. The sensors are bonded to each other and to the pitch adapter with the wire wedge bonding technique, using standard commercial wire bonding machines.
In addition to the already mentioned variety of module types (number of strips, single- or double-sided, one or two sensors), the geometry of the wedge-shaped TEC modules has been optimized individually for each ring for optimal geometrical coverage using 6” wafers while maintaining cost-effectiveness. This has led to ten different module types in the TEC, each of which needed specific custom precision jigs for assembly and wire-bonding. The TEC modules were produced by four gantry centers and seven bonding centers, which typically assembled/bonded three and one or two module types, respectively. This distributed production with a high level of specialization of the centers made the production very inert and inflexible. In addition, the ramp-up time and learning curve within each center has to be accounted for.
The TEC module production was also slowed down by technical problems. The bias voltage is delivered to the sensor back plane via a Kapton strip, and the contact between the back plane and the gold surface of that strip used to be realized with silver epoxy glue. It was found that this method did not provide the desired reliability. Especially after thermal cycling, increased contact resistances and even open contacts were observed. This led to the decision that the bias contact must be wire-bonded, a major change of the production scheme in the middle of the production. Almost all modules produced until then have been reworked according to the new method.
The TEC module production was completed in August 2006.

3 Petal Production

TEC modules are mounted in seven radial rings onto support plates, the petals [2]. The petal itself is a very light but stiff structure consisting of a honeycomb core with two carbon fiber skins glued to each side. Cooling is provided by means of a 7 m long titanium cooling pipe with an inner diameter of 3.4 mm, through which the coolant C_6F_{14} is flushed. Each module is screwed onto up to four aluminium inserts that are milled to a relative mechanical precision of 5 μm and are glued to the cooling pipe, thus providing the thermal contact. Two petal bodies were built per day.
Assembled petals are very complicated objects, with several motherboards, up to 28 modules of 10 types and up to 28 Analog Opto-Hybrids (AOHs) of 13 types mounted onto the petal using about 400 assembly pieces. The petal assembly was factorized into AOH assembly, done by one specialized center, and module assembly, performed in five petal integration centers. A software was developed to guide technicians through the complicated assembly procedure. Petal assembly took about one day per petal per center. Challenges during assembly were the handling of fragile optical fibers and modules in a very dense environment, making the exchange of faulty components a time consuming and risky operation.

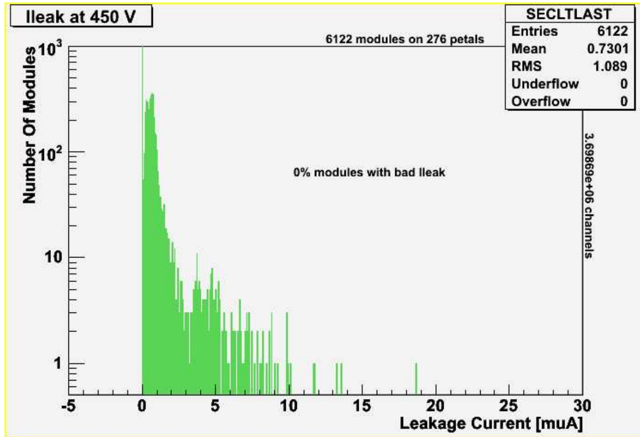

Figure 3: Leakage current (in μA) of 6122 modules on 276 petals measured during the long-term test at a bias voltage of 450 V.

Assembled petals were then subjected to a long-term test, in which they underwent six temperature cycles between room temperature and $-20°$C within three days. Mean silicon temperatures of $-20°$C and mean hybrid temperatures of $-3°$C and $-11°$C for modules with six and four APVs, respectively, were typically reached during the test. A deep electrical characterization of the petals was performed during several readout tests at room temperature and in the cold environment, and the petals were graded according to certain quality criteria. In Fig. 3 the leakage current of all 6122 modules of 276 petals, as measured with the dedicated slow control ADC (Detector Control Unit, DCU) located on the hybrid, is shown. All modules fulfill the requirement of a leakage current below 10 μA per sensor. Figure 4 shows the common mode subtracted noise of about 3.7 million strips on 276 petals in deconvolution mode, normalized to the mean of the distribution. The quality of the produced petals is excellent: the fraction of dead or noisy strips is 1 ‰ in total. APV edge strips show generally an increased noise and have to be treated differently using other criteria in addition (unfilled histogram in Fig. 4). The fraction of dead or noisy strips per petal, excluding APV edge strips, amounts to 1-2 ‰.
About seven petals have been long-term tested per week. In September 2006 the petal production was completed. While the petal design made it possible to distribute the production of medium-sized structures across various institutes, a large amount of bookkeeping and detailed planning was necessary to have all parts available in all five petal integration centers on time. In addition, risky shipments of modules and petals were necessary on a daily basis.

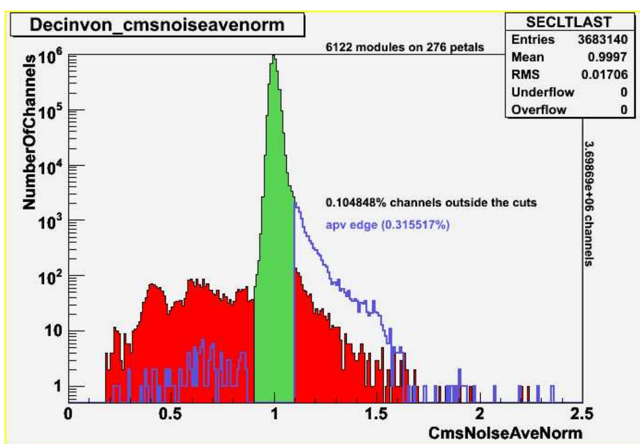

Figure 4: Common mode subtracted noise of about 3.7 million strips on 276 petals during the long-term test, in deconvolution mode. The noise was normalized to the mean of the total distribution. Strips in the light grey region are flagged as good, strips outside are flagged as noisy or dead if they are no APV edge strips (dark grey histogram, 0.1 %). For APV edge strips (unfilled histogram), other criteria are used in addition for the flagging.

4 TEC Integration

The concept of petals as self-contained and pre-tested objects simplified the task of TEC integration a lot. The TEC structure itself was fully assembled and equipped with services (cooling pipes and cables) before any petals were inserted. During integration, each TEC was mounted in a cradle that allowed for full rotation of the whole structure around the x axis. The TECs were integrated sector-wise, where one sector corresponds to one eighth of a TEC in ϕ and comprises nine front and nine back petals with together 400 modules. In Fig. 2 one sector is indicated.

The TECs were oriented horizontally during integration. Nine petals were routinely installed per day, using a custom made mechanical tool that implemented a camera so that each step, even deep inside the TEC structure, could be watched. Due to details of their fixation, back petals have to be inserted before their neighbouring front petals, and petals can only be inserted when located above the disks. While the modular petal design has the advantage that single faulty petals can be exchanged at any time, back petals can only be removed after removal of the neighbouring front petal, including a rotation of the TEC. After insertion, 944 optical fibers have to be cleaned and connected per sector, a risky and time-consuming task. Investigations of problems and repair or even exchange of components with the petals installed is impossible.

After installation of one sector, the petals are fully characterized at room temperature during a 5-day readout period, including tests of communication stability, tuning of the APV and AOH parameters to find the optimal working point, recording of pedestals, ramping of the bias voltage up to 450 V, readout of slow control parameters via the DCU and a check of all temperature and humidity sensors located on the petals. For TEC+, roughly 70 000 cosmic muon events have been recorded for each sector. At the time of the conference (September 2006) eight and four sectors were installed and five and two sectors were fully qualified in TEC+ and TEC−, respectively.

The performance of petals inside the TECs is excellent. In Fig. 5 the mean noise of each APV of a typical sector of TEC+ is plotted versus the APV number, where the 1888 APVs are ordered such that first front petals of disks 1 to 9, then back petals of disks 1 to 9 are displayed. For each petal, the modules are ordered with increasing ring number, i.e. with increasing radial distance to the beam line. Since from inside to outside the strip length increases, the noise increases with the ring number for each petal. Good uniformity is found for the petals of a sector.

The common mode is calculated assuming a constant value per APV. In Fig. 5 the difference between raw and common mode subtracted noise is barely visible. The mean common mode noise per APV has been compared to the mean intrinsic (common mode subtracted) noise per APV, and was found to amount to 20 % of the intrinsic noise (Fig. 6). The flatness of the noise is an indicator of the quality and robustness of the grounding scheme. As a measure of the flatness, the ratio of the RMS of the common mode subtracted noise to the mean noise, both again calculated per APV, is used. The distribution of this ratio is shown in Fig. 7 for one sector of TEC+ in deconvolution mode. The relative spread of the noise amounts to about 2.7 %.

In Fig. 8 the common mode subtracted noise of the 46 464 strips of all ring 7 modules of one sector of TEC+ is shown for deconvolution mode. To be independent of the gain of the optical chain, the analog output was normalized to the height of the digital APV output signal. Apart from very few dead or noisy strips, the tails are negligible.

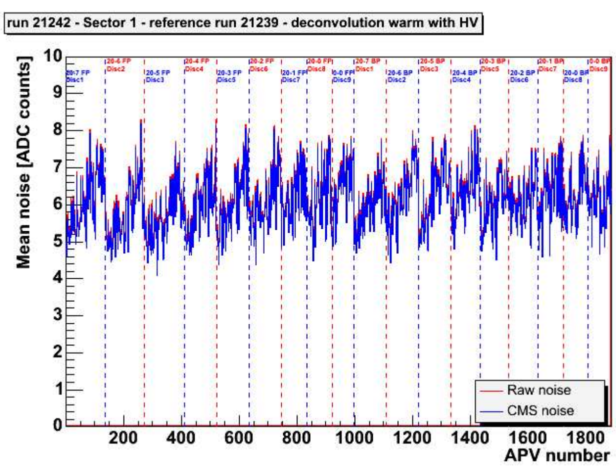

Figure 5: Mean raw (light grey histogram) and common mode subtracted (dark grey histogram) noise of each APV versus APV number, in deconvolution mode, for sector 1 of TEC+. First front petals of disks 1 to 9, then back petals of disks 1 to 9 are displayed. Within each petal, the modules are ordered with increasing ring number.

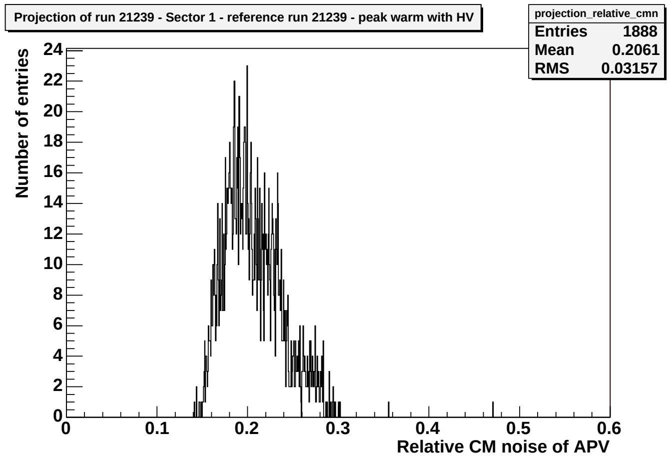

Figure 6: Distribution of the ratio between the mean common mode noise per APV and the mean intrinsic noise per APV, in deconvolution mode, for all APVs of sector 1 of TEC+.

Other sectors show a similar performance.
Typically 1 ‰ of dead or noisy strips are found per sector. However, localized defects such as dead fibers (0.4 ‰) or malfunctioning front-end chips (0.7 ‰) lead to an inefficiency of typically 2-3 ‰ per sector (all quoted numbers are for the five qualified sectors of TEC+).
For TEC+ cosmic muon data are recorded for each sector. Most probable values for the signal-to-noise ratio of 26 for thin sensors and 32 for thick sensors have been observed in peak mode, using a rough timing adjustment, common for the whole sector. The cosmic muon data sets proved invaluable for cross-checking of the implementation of the TEC geometry in the tracking software. Track alignment methods are currently being studied with the cosmic data from the integration.

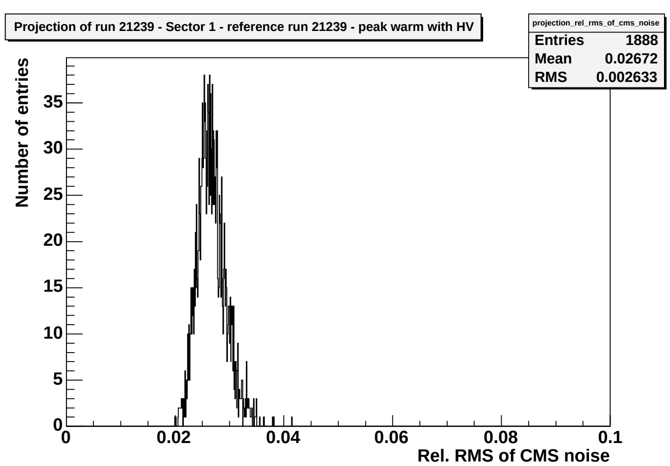

Figure 7: Distribution of the ratio between the RMS and the mean of the common mode subtracted noise per APV, in deconvolution mode, for sector 1 of TEC+.

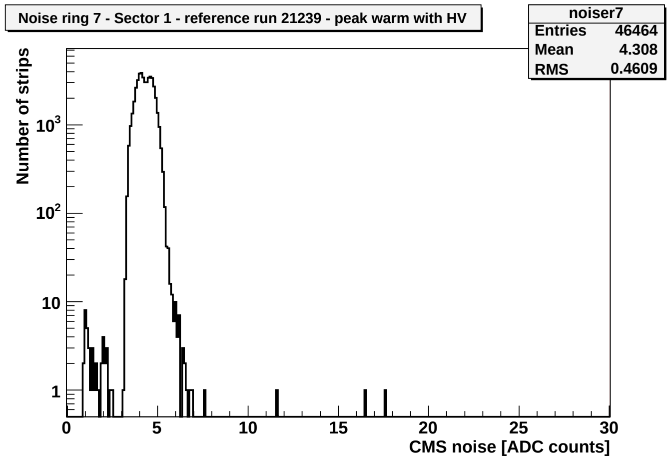

Figure 8: Common mode subtracted noise in deconvolution mode for all strips of all ring 7 modules of sector 1 of TEC+.

5 Summary

In this article the status of the CMS tracker end cap production and integration was reviewed, and challenges were discussed. Module and petal production are finished, and the integration of the TECs is far advanced. Excellent performance of petals both outside and inside the TECs has been observed, with typically 1 per mille of dead or noisy strips per petal. The noise performance of integrated petals is excellent. A cold test of the TECs will start in November 2006.

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