Design and construction of the CMS Outer Tracker for the Phase-2 Upgrade

Irene Zoi[1]

Fermi National Accelerator Laboratory,
Batavia, IL, USA

Abstract

The High-Luminosity LHC (HL-LHC) is expected to deliver an integrated luminosity of 3000–4000 fb^{-1} over 10 years of operation with the peak instantaneous luminosity reaching about 5–7.5×$10^{34}cm^{-2}\,s^{-1}$. During Long Shutdown 3, several components of the CMS detector will undergo major improvements, called Phase-2 upgrades, to be able to operate in the challenging environment of the HL-LHC. The current CMS tracker will be replaced. The Phase-2 Outer Tracker (OT) will have increased radiation tolerance, higher granularity, and the capability to handle higher data rates. Moreover, the OT will provide tracking information to the Level-1 trigger for the first time at a hadron collider, allowing trigger rates to be kept at a sustainable level without sacrificing physics potential. For this, the OT will be made of modules with two closely-spaced silicon sensors read out by front-end ASICs that can correlate hits in the two sensors to create short track segments, used in the Level-1 track finder. The modules come in two flavors: strip-strip and pixel-strip, containing different sensor configurations and multiple ASICs. This contribution presents the Phase-2 OT, the finalization of the OT module design, and the quality assurance and control procedures used to ensure that the modules fulfill both the specifications from the assembly steps as well as the proper communication among the ASICs.

Keywords: Silicon sensors, strip sensors, pixel sensors, tracking detectors

1. Introduction

The CERN LHC [1] will be upgraded to the High-Luminosity LHC (HL-LHC) [2] during the Long Shutdown 3 (LS3). The maximum instantaneous luminosity will be increased to reach up to $7.5 \times 10^{34}cm^{-2}s^{-1}$ and over the 10 years of data taking a total luminosity of 3000 – 4000 fb^{-1} will be collected.

The CMS detector [3] was designed for instantaneous luminosities of $1 \times 10^{34}cm^{-2}s^{-1}$ and an average of 20 to 30 simultaneous proton-proton collisions per bunch crossing (pileup), which is expected to increase to 200 at the HL-LHC. To cope with the increased pileup and radiation damage and to maintain its performance, the CMS detector will be significantly improved in the context of the so-called Phase-2 upgrade [4]. The current strip tracker will be replaced by a new system called Outer Tracker (OT) [5]. The key features of the modules to be used in the OT will be described in this contribution.

Due to the high collision rate of the LHC, the amount of data generated by the CMS detector is too large to be completely stored on disk and a two-level trigger decision system is used. The first level, or Level-1 (L1) trigger, [6], based on custom-made fast electronics with inputs from some of the CMS sub-detectors, decides at 40 MHz which events are interesting enough to be read out from the detector for further processing. Simulations show that by using the current L1-trigger strategy, based on calorimeters and muon detectors alone, the current trigger thresholds cannot be maintained as the L1 accept rate would be well above the allowed maximum of 750 kHz. By including tracking information at L1 it will be possible to maintain the thresholds and thus maximize the physics potential of the upgraded CMS detector. The 3.8 T solenoidal magnetic field of CMS causes curvature in charged particle trajectories, enabling discrimination based on transverse momentum (p_T). A so-called p_T-module of the OT has two closely spaced silicon sensors read out by the same electronics. The spacing between the two sensors varies with the location in the detector and has been optimized to guarantee, together with a programmable acceptance window in the front-end ASICs, a consistent p_T threshold across the entire OT volume [5]. Only particles with high p_T (small curvature) will produce two closely-spaced hits on the two sensors, from which the module front-end electronics forms a track segment, called a stub. A target p_T threshold of 2 GeV is sufficient to allow transmission of the stubs to the off-detector electronics at the full 40 MHz bunch crossing rate. Once the global L1 decision is taken, the entire detector is read out at full granularity, including the OT hit information. These data are buffered on detector for up to 12.5 μs before they are sent to the central Data Acquisition system for use in the High-Level Trigger, which is implemented on a computing farm built from commercially available CPUs and GPUs.

The p_T-modules come in two different flavors: strip-strip (2S) and pixel-strip (PS) modules, which will be described in Section 2 and Section 3, respectively. Section 4 will detail the module qualification procedure during the production while Section 5 describes the mechanical layout of the OT and the key

*Corresponding author
Email address: irene.zoi@cern.ch (Irene Zoi)
[1]for the Tracker Group of the CMS Collaboration

design elements contributing to the reduced material budget.

2. 2S modules

The OT will require 7608 strip-strip modules which will be assembled by seven production centers in Belgium, Germany, India, Pakistan, and the US.

2S modules are composed of two strip sensors of 10×10 cm^2 divided into two rows of 5 cm long strips with a pitch of 90 μm. The design of the 2S module is shown in Fig. 1. For each row, both strip sensors are read out by 8 CMS Binary Chips (CBC) [9] which also perform the stub finding. The stubs as well as triggered data are sent at 320 MHz to the Concentrator Integrated Circuit (CIC) [10], which aggregates data from 8 CBCs and performs clustering and zero suppression of the triggered data. Data are then sent to the Low-power GigaBit Transceiver (LpGBT) [11]. The LpGBT receives stubs and triggered data from the two halves of the module and sends them at 5.12 Gb/s to the Versatile TRansceiver plus (VTRx+) [12], which converts the data into an optical signal and transmits them to the back-end electronics. Fast commands, such as clock, L1 accept signals, and fast rest commands as well as slow commands such as programming data, are sent via fiber optics by the back-end electronics to the VTRx+ at 2.56 Gb/s. They are converted into an electrical signal, and passed to the LpGBT. The programming of the front-end chips is done via the LpGBT using the I2C protocol.

The CBC and CIC ASICs are bump-bonded to Front-End Hybrids (FEH) printed-circuit boards which are located on the two sides of the module. The FEH is folded on itself and features wire-bond pads for the top and bottom sensor, allowing the CBC to read out both of them. A Service Hybrid (SEH) hosts the LpGBT and the VTRx+. On the same hybrid, a two-stage DC/DC conversion is used to step down an input voltage of 10 V to the voltages needed for the ASICs. This approach reduces the current in the power cables, allowing the low-voltage cable cross-section to remain comparable to that of the current tracker, despite higher power consumption, thus avoiding an increase in the material budget. Strip sensor separation is provided by aluminum-carbon fiber bridges that are produced for 1.8 mm and 4.0 mm module thickness.

A set of 21 prototypes, called *kick-off* modules, produced by different assembly centers, has been used to validate and finalize the design of the hybrids before the start of the production. In particular, two different layouts for the SEH were produced: a Common (ground) Plane variant with a single ground layer for DC outputs and switching power currents, and a Split Plane variant with separate DC ground and switching current ground layers, linked at a common point [18]. Moreover, the effect of introducing a ground balancer (GB) directly connecting the ground levels between the two FEHs was evaluated.

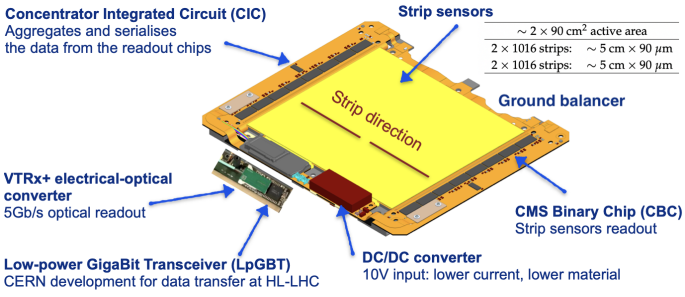

Figure 1: 2S module design.

The results of the studies conducted on the kick-off modules are presented in Fig. 2. The Common Plane grounding scheme was selected as the final module design as it demonstrated the best noise performance. The production 2S modules will also include a ground balancer, as illustrated in Fig. 1, to equalize ground and powering lines between the two FEHs.

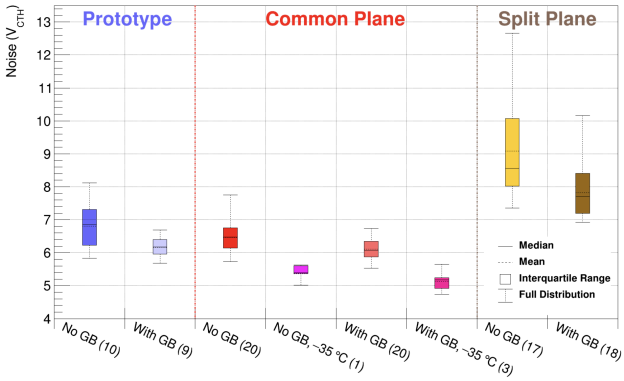

Figure 2: Noise measurements with prototype and kick-off modules performed at −350 V bias voltage, either at room temperature or at -35°C. Common Plane and Split Plane refer to the Service Hybrid version used in the kick-off modules. The boxes represent all individual channel noise measurements and include measurements from several modules; the numbers of modules is indicated in parentheses.

3. PS modules

The OT will host 5592 PS modules which will be assembled in five production centers in Germany, Italy, and the US.

PS modules are composed of one strip sensor (PS-s) and one macro-pixel sensor (PS-p). A sketch of the PS module is shown in Fig. 3. The PS-p sensor, located on the bottom side of the module, is 5×10 cm^2 in size. It features macro-pixels of 1.5 mm $\times$ 100 μm and is read out by 16 Macro Pixel ASICs (MPA) [14] bump-bonded to it. The PS-s sensor has the same dimensions, featuring two rows of 2.4 cm long strips with a pitch of 100 μm. Short Strip ASICs (SSA) [15] read out the strip sensor (8 per side) and send clustered hits to their respective MPAs which correlate them with pixel clusters to form stubs. The MPAs output stubs at 40 MHz and transmit strip and pixel hit data once a L1 trigger has been received. In PS modules, zero suppression and clustering of the pixel hits are performed by the MPA. The rest of the readout chain is the same as on the 2S modules: data from the 8 MPAs reading one half of the module go to a CIC, which aggregates and forwards them to the LpGBT. Data are transmitted optically to and from

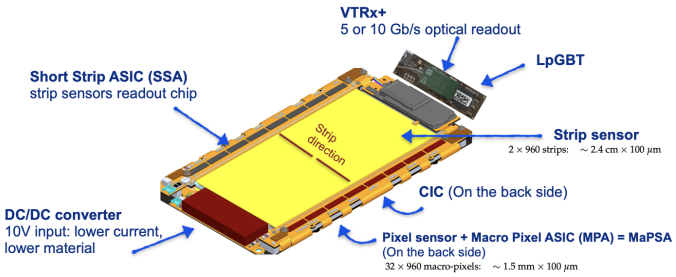

Figure 3: PS module design.

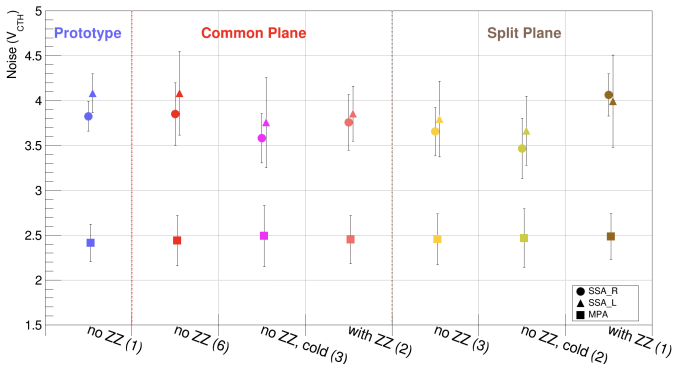

Figure 4: Noise measurements with prototype and kick-off modules performed at varying bias voltages all above full depletion, either at room temperature or below -20°C (cold), and with or without the zigzag-cable (ZZ). The symbols represent the mean (the bars represent one standard deviation of the distribution) of all channels grouped by hybrid and sensor; the numbers of modules are indicated in the parentheses. SSA_L and SSA_R refers to measurements of the strip sensor connected to the SSA chips of the left or right hybrid, respectively. MPA refers to measurements of the pixel sensor connected to the MPA chips.

the back-end electronics using the VTRx+. To cope with higher data rates in the inner part of the detector, the PS module can be operated with the CIC transferring data at 640 MHz and the LpGBT operating at 10.24 Gb/s. Where lower data rates are expected, the PS module will operate at 5.12 Gb/s. SSA and CIC ASICs are located on the left and right front-end hybrids (FEH), while the LpGBT and VTRx+ are placed on the read-out hybrid (ROH). PS modules are also equipped with a power hybrid (POH) hosting the DC/DC converters.

PS modules will be produced with three sensor separations of 1.6 mm, 2.6 mm, and 4.0 mm provided by aluminum nitride spacers.

Also for this module type, 14 kick-off modules, produced among the different assembly centers, were used to validate and finalize the design. Two POH variants, Common Plane and Split Plane as described in Sec. 2, and the removal of an additional 'zigzag' powering tail (ZZ) connecting the POH and the ROH were investigated.

The results of the studies conducted on the kick-off modules are presented in Fig. 4. No significant performance difference was observed with the two POH designs, the Common Plane grounding scheme was selected as for the 2S modules. As no performance improvement was seen, the additional powering tail will not be used to simplify the assembly procedure.

4. Module qualification

More than 100 prototype and kickoff modules have been assembled across multiple production sites, allowing them to verify assembly procedures and control processes.

Several tests have been performed on these modules to verify their functionality, both in the laboratory and with particle beams, both before and after irradiation up to end-of-life fluences. A complete set of quality control tests is implemented for the modules and their components [16, 17].

One of the most critical aspects of the p_T-module design is the alignment between the two sensors since stub reconstruction relies on the parallelism of the strips and pixels in the two sensors. Dedicated fixtures ensure that the alignment specifications are met. For 2S modules, the rotational misalignment must be less than 400 μrad, and for PS modules, less than 800 μrad. For both module types, the allowed offsets are less than 100 μm along the strip direction and less than 50 μm perpendicular to it. If the sensor sandwich satisfies the specifications, the hybrids are added and the sensors are wire-bonded to the corresponding lines on the hybrids. After a quick electrical test to verify that all channels are connected, the wire bonds are encapsulated. This makes handling of the module safer and prevents discharges between the sensor edges and the electronics. The main assembly steps are described in Ref. [13]. Once the module assembly is completed, a more detailed quality control is carried out. Module production sites are equipped with dedicated test stands and burn-in setups for module qualification. All modules are required to go through multiple thermal cycles from room temperature to operation temperature (around -35°C) over 24 hours to screen for early-life failures. During this time modules will also undergo various calibrations, including noise measurements, communication tests between module ASICs and verification of the stub logic functionality. Examples of these measurements are shown in Fig. 5. Based on these results, each module will be graded and its characteristics stored in the production database. These data will be then used to identify the best modules to be installed in the detector.

5. Outer Tracker layout and mechanics

The OT is composed of a barrel and two endcaps. The chosen layout guarantees that every particle originating from the interaction point with $|\eta| < 2.4$ will cross at least six modules.

The barrel is composed of six layers, the innermost three (radius < 60 cm) equipped with PS modules (Tracker Barrel PS or TBPS) and the outer three (radius > 60 cm) with 2S modules (Tracker Barrel 2S or TB2S).

The TBPS has two sub-parts. In the central section PS modules are mounted on both sides of a ladder-like support, called *plank*. The other part is composed of rings supporting modules with progressively increasing tilt angles. This design choice guarantees high reconstruction efficiency while reducing the number of module used and hence material budget, as explained

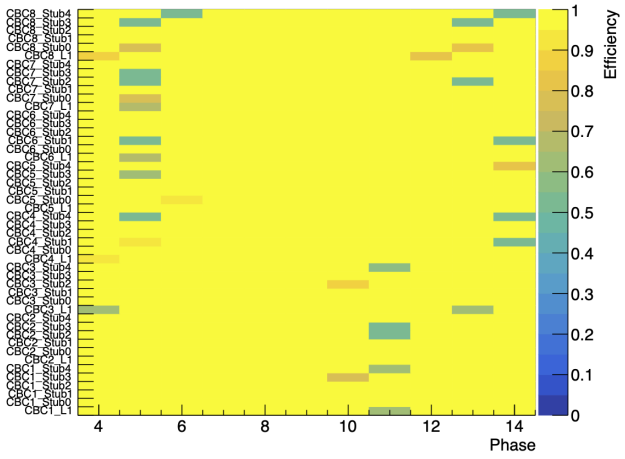

Figure 5: A scan of the CIC sampling phases on all 48 CBC data lanes on a 2S FEH. The phase steps are about 390 ps, corresponding to 1/16 of two 320 MHz clock cycles. Sampling phases where communication is error-free (yellow) and where errors are detected (non-yellow) are shown. A wide range of phases providing reliable communication is visible.

in Ref. [5]. In both parts, modules are mounted on alternating sides of the supporting structure to ensure hermetic coverage. The TB2S is composed of *ladder* structures where modules are placed in a similar arrangement to the one used for the TBPS planks. Ladders are then arranged in a support wheel to form cylindrical layers. The two endcaps are formed by five double-discs (Tracker Endcap Double Discs or TEDD). Each double-disc is composed of four D-shaped parts, referred to as dees, and modules are mounted such that overlap is guaranteed in a double-disc. PS modules are used in the inner part (radius < 60 cm) and 2S modules in the outer (radius > 60 cm).
Simulations show that 2S (PS) modules will face a fluence up to 4.9×10^{14} n_{eq}/cm^2 (1.4×10^{15} n_{eq}/cm^2) after an integrated luminosity of 4000 fb^{-1} [7]. To keep the effects from radiation damage at bay, the OT will be operated at sub-zero temperatures through the use of bi-phase CO_2 system. This allows for the use of small-diameter low-mass pipes which helps to reduce the material budget. The temperature on the individual modules during operation will be around -35°C.

The material budget of the OT is further reduced when compared to the current system, especially for $1 < |\eta| < 2$, through the use of point-of-load DC/DC converters, a better service routing, and the tilted layout of the TBPS.

6. Conclusions

The CMS Phase-2 Outer Tracker will provide excellent tracking performance at the HL-LHC thanks to an increased granularity, a reduced material budget and increased radiation hardness. Additionally, it will be able to identify hits from high-p_T tracks on detector and provide this information to the L1-trigger system. Several production centers in Europe, the US, and Asia will be involved in the multi-step assembly of more than 13 000 modules required for the Outer Tracker. Numerous prototypes have been built to fine-tune the assembly lines and testing procedures for the module production, which is expected to start in 2025. Studies performed on kick-off modules have allowed the validation and finalization of the module design before the start of production. Mechanical structures designed to guarantee hermetical coverage while minimizing the material budget will host the modules and first integration tests were successful. With this upgrade, the CMS detector is expected to maintain high performance throughout the full HL-LHC data-taking period.

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