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

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The High Luminosity LHC (HL-LHC) is expected to deliver an integrated luminosity of $3000-4000\ \mathrm{fb}^{-1}$ after 10 years of operation with peak instantaneous luminosity reaching about $5-7.5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. During Long Shutdown 3, several components of the CMS detector will undergo major changes, called Phase-2 upgrades, to be able to operate in the challenging environment of the HL-LHC. The current CMS silicon strip tracker has to be replaced with a new detector. The Phase-2 Outer Tracker (OT) will have high radiation tolerance, higher granularity and the capability to handle higher data rates. Another key feature of the OT will be to provide tracking information to the Level-1 trigger, allowing trigger rates to be kept at a sustainable level without sacrificing physics potential. For this, the OT will be made out of modules which have two closely spaced sensors read out by front-end ASICs, which can correlate hits in the two sensors creating short track segments, called stubs. The stubs will be used for tracking in the L1 track finder. In this contribution, the design of the CMS Phase-2 OT, the technological choices and first results with prototype devices are reported.

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1. Introduction

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

The Compact Muon Solenoid (CMS) detector [3] was initially designed for instantaneous luminosities of $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ and an average of 20 to 30 simultaneous proton-proton collisions per bunch crossing (pileup). At the HL-LHC the pileup will increase up to 200 collisions per bunch crossing. To cope with the increased pileup and radiation damage and to maintain high physics performance, the CMS detector will be significantly upgraded [4] as part of the so-called Phase-2 upgrade. In particular, the current silicon tracker will be entirely replaced due to unacceptable performance degradation beyond about 1000 fb^{-1} [5]. This paper describes the key features of the Phase-2 Outer Tracker (OT).

In the CMS experiment, the amount of data received by the detector is too large to be completely stored on disk and a two-level trigger decision system is used. The first layer, Level-1 (L1) [6], based on custom-made fast electronics, decides at 40 MHz which events are interesting enough to be read out from the detector for further processing, based on inputs from some of the CMS sub-detectors. The second trigger stage, the High Level Trigger (HLT) [7], based on commercial computers, runs a simplified reconstruction on those events and decides which ones are to be stored on disk for analysis. Simulations show that by using the current L1-trigger strategy, based on calorimeters and muon detectors, the overall trigger rates will be well above the allowed maximum rate in Phase-2 of 750 kHz and reconstruction algorithms will have sub-optimal performance. It is therefore critical for the CMS data taking at the HL-LHC that the OT provides information to the L1 trigger, employing p_T-modules, whose design is described in the next sections. A p_T-module has two closely spaced silicon sensors read out by the same electronics. The 3.8 T solenoidal magnetic field of CMS allows to discriminate on the particle transverse momentum (p_T) based on the curvature: only particles with high p_T (small curvature) will produce two closely separated hits on the two sensors, and generate a track segment, called *stub*, which is identified by the module front-end electronics. The spacing between two sensors depends on the location of the module in the detector and was optimized based on simulations to guarantee, in addition to a programmable acceptance window in the front-end ASICs, a coherent p_T filtering in the whole Outer Tracker volume [5].

The target p_T threshold is 2 GeV, which corresponds to a data volume reduction of roughly one order of magnitude. This is sufficient to enable transmission of the stubs to the off-detector electronics at the full 40 MHz bunch crossing rate.

The p_T-modules come in two different flavors: strip-strip (2S) and pixel-strip (PS) modules, which will be described in Section 3 and Section 4, respectively.

2. Outer Tracker layout and mechanics

The Outer Tracker is composed of a barrel and two endcap regions. The chosen layout guarantees that every particle originating from the interaction point with $|\eta| < 2.4$ will cross at least

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six modules. A sketch of the Outer Tracker design is shown in Fig. 1.

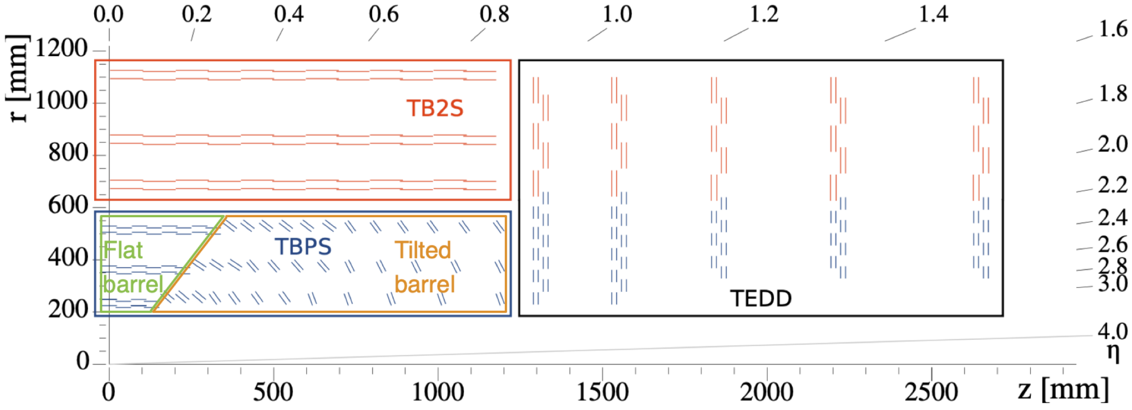

Figure 1: Sketch of one quarter of the Outer Tracker. PS and 2S modules are represented in blue and red, respectively.

The barrel is composed of six layers, the innermost three (radius < 60 cm) equipped with PS modules (Tracker Barrel PS or TBPS) and the outermost three (radius > 60 cm) with 2S modules (Tracker Barrel 2S or TB2S). The TB2S is composed of *ladder* structures: modules are placed in a row, mounted on both sides of the ladder alternately to guarantee overlap between modules and thus hermeticity. Ladders are then arranged in a support wheel to form cylindrical layers. The TBPS has two sub-parts with different characteristics. In the central section PS modules are mounted on *planks* in a similar arrangement to the one used for the TB2S ladders. The other part is composed of rings supporting modules with progressively increasing tilt angles. In each ring, modules are installed on the two sides of the supporting structure, alternated to achieve hermetic coverage. This design choice guarantees high reconstruction efficiencies while reducing the number of module used, as explained in Ref. [5]. 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 located such that overlap is guaranteed once these components are assembled into the double-disc: PS modules are used in the inner part (radius < 60 cm) and 2S modules in the outer one (radius > 60 cm).
Simulations show that 2S (PS) modules will face a radiation 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} [8]. To keep the effects from radiation damage at bay, the OT will be operated at low temperatures with a cooling based on bi-phase CO_2. This system also enables the use of small-diameter and low-mass tubing 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 through the use of point-of-load DC/DC converters, a better service routing, and the tilted layout of the TBPS. A clear improvement in terms of material budget is visible, especially for $1 < |\eta| < 2$, when comparing the Phase-1 [9] and Phase-2 trackers, as shown in Fig. 2.

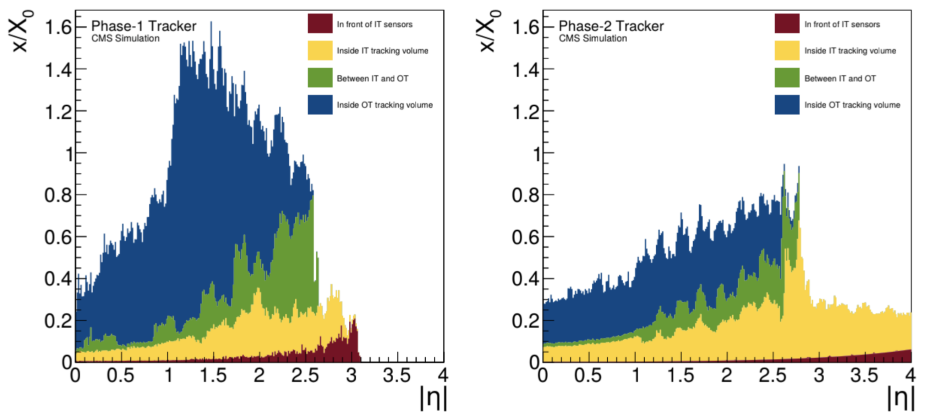

Figure 2: Material budget inside the tracking volume estimated in units of radiation lengths, as a function of pseudorapidity, comparing the Phase-1 (left) and the Phase-2 (right) detectors [5]. The contributions from the different components are stacked and shown in different colors.

3. 2S modules

2S modules are composed of two strip sensors with dimensions of $\sim 10 \times 10$ cm^2 hosting two rows of 5 cm long strips with a pitch of 90 μm. The design of the 2S module is shown in Fig. 3. Each of the two strip sensor rows is read out by 8 CMS Binary Chips (CBC) [10] which also reconstruct the stubs. Stubs and hit data are sent at 320 MHz to the Concentrator Integrated Circuit (CIC) [11], which aggregates data from the CBCs and performs clustering and zero suppression of the triggered data. Data are then sent to the Low Power GigaBit Transceiver (LpGBT) [12]. 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+) [13] which converts the data into an optical signal and transmits it to the back-end electronics. Fast commands (i.e. L1 accept, clock, reset) and slow commands are sent via fiber optics by the back-end electronics to the VTRx+ at 2.56 Gb/s, converted into an electrical signal, and passed to the LpGBT. The programming of the front-end chips is done via I2C using the LpGBT I2C functionality.

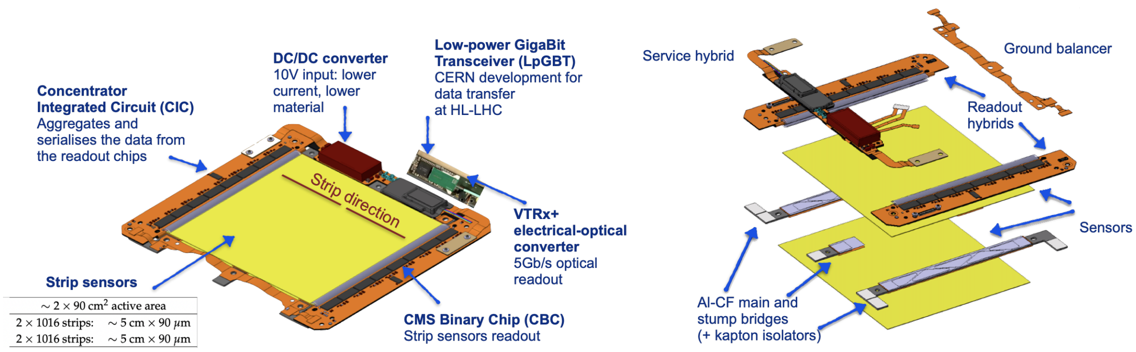

Figure 3: 2S module design (left) and exploded view (right).

The CBC and CIC ASICs are bump-bonded to Front-End Hybrids (FEH) which are located on the two sides of the module. The FEH is folded on itself and features wire-bonding pads for the two sides of the module, allowing the CBC to read out signals from the top and the bottom strip sensors. Adjacent to the strips, the Service Hybrid (SEH) hosts the LpGBT and the VTRx+. On the same hybrid, a two-stage DC/DC conversion is used to transform the 10 V input to the voltages used to power the ASICs on the module. This feature reduces the current flowing to the modules, allowing for a smaller cross-section of the low voltage cables and therefore reducing the material budget. A ground balancer is placed on the opposite side of the module to equalize ground and powering lines between the two FEHs. Strip sensor separation is guaranteed by Aluminum-Carbon Fiber (Al-CF) bridges that are produced for 1.8 mm and 4.0 mm module thicknesses. The material choice was driven by its high thermal conductivity, low density, a coefficient of thermal expansion close to that of silicon, and the cost of the 3D machining.

3.1 2S module assembly

The OT detector will require 7 608 strip-strip modules which will be assembled by seven production centers in Belgium, Germany, India, Pakistan, and the US. The main assembly steps are described below and in Ref. [14].

Kapton isolators are attached to the strip sensors before assembly to prevent electrical contact between the sensor backside and the Al-CF bridges. High voltage is provided via tails glued and wire-bonded to the sensor backside that allow connection to the service hybrid. 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. Dedicated fixtures ensure that the alignment specifications are met: rotation less than 400 μrad, offset parallel (perpendicular) to the strip less than 100 μm (50 μm). If the sensor sandwich satisfies the specifications, the left and right FEHs, the SEH and the ground balancer are glued on the Al-CF bridges and the strips of the sensors are wire-bonded with the corresponding lines on the hybrids. After wire bonding is completed, the wire-bonds are encapsulated once a quick electrical test has verified that all channels are connected. This makes handling of the module safer and prevents discharges between the sensor edges and the electronics. At this point, the module assembly is completed and a more detailed quality control is carried out.

4. PS modules

PS modules are composed of a macro-pixel and a strip sensors. A sketch of the PS module is shown in Fig. 4. The pixelated sensor (PS-p), located on the bottom side of the module, is 5×10 cm^2 in size, features macro-pixels of ~ 1.5 mm $\times$ 100 μm and is read out by 16 Macro Pixel ASICs (MPA) [15] bump-bonded to it. The top layer is made of a strip sensor (PS-s) with the same dimensions and 2.4 cm long strips with a pitch of 100 μm. Sixteen Short Strip ASICs (SSA) [16] read out the strip sensor and send the clusters to the respective MPAs, which combine this with the pixel information to form the stubs. In PS modules, zero suppression and clustering are done 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 the back-end electronics using the VTRx+. To cope with higher

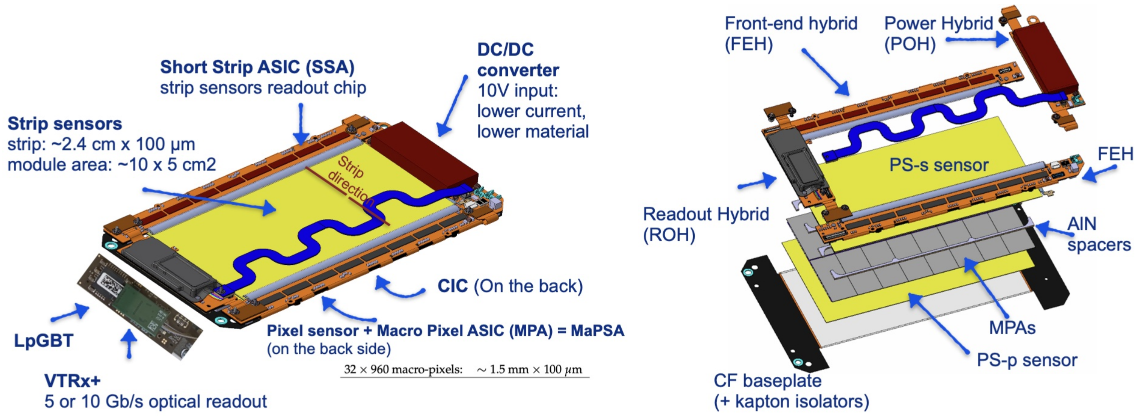

Figure 4: PS module design (left) and exploded view (right).

data rates in some parts of the detector, the PS module can be operated with the CIC transferring data at 640 MHz and the LpGBT transferring data 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 on the readout 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, 1.6, 2.6, and 4.0 mm maintained by aluminum nitride (AlN) spacers, since they do not need 3D machining. While the other properties of this material are similar to AlCF used in the 2S modules bridges, AlN is less fragile and is an electrical isolator, simplifying the PS module assembly.

4.1 PS module assembly

The OT will host 5 592 PS modules which will be assembled in five production centers in Germany, Italy and the US. The main assembly steps are described below and in Ref. [14].

The module is built on a CF baseplate that needs to be prepared: aluminum inserts for precision positioning in the detector are glued and a Kapton layer is attached to prevent electrical contact between the CF and the pixel sensor. As for the 2S case, a tail for providing the high voltage is glued and wire-bonded to the backside of the strip sensor. The sub-assembly consisting of the pixelated sensor bump-bonded to the MPAs (Macro Pixel Sub-Assembly or MaPSA) does not require further processing and is ready to be assembled on the module as soon as quality control is passed. For the gluing of the sensor sandwich two approaches are possible and adopted in the production centers, either using a robot combined with a pattern recognition camera or a manual fixture. The rotational misalignment is required to be less than 800 μrad and parallel (perpendicular) offsets with respect to the strip direction must be less than 100 μm (50 μm). Next, the hybrids are glued to the CF baseplate on which the sandwich is attached. Once the glue has cured, the hybrids are wire bonded to the strip sensor and the MPAs. After a quick test to verify the wire-bonding quality, the top and bottom wire-bonds are encapsulated and the module is ready to go through quality control.

5. Module testing, integration and quality assurance

More than 60 (30) 2S (PS) prototypes have been assembled across the various production sites, allowing them to verify their assembly procedures and control processes. Several tests have been performed on these devices both in the laboratory and with particle beams, both before and after irradiation up to end of life fluences, confirming the expected performance. In particular, the stub reconstruction mechanism was verified in test beam campaigns, emulating the curvature induced by the magnetic field by rotating the module with respect to the beam direction. The efficiency as a function of the emulated p_T or angle is shown in Fig. 5. The expected sharp turn-on of the stub reconstruction efficiency is observed in correspondence to the p_T threshold, whose value can be selected by modifying the window in which the hits are correlated to produce a stub.

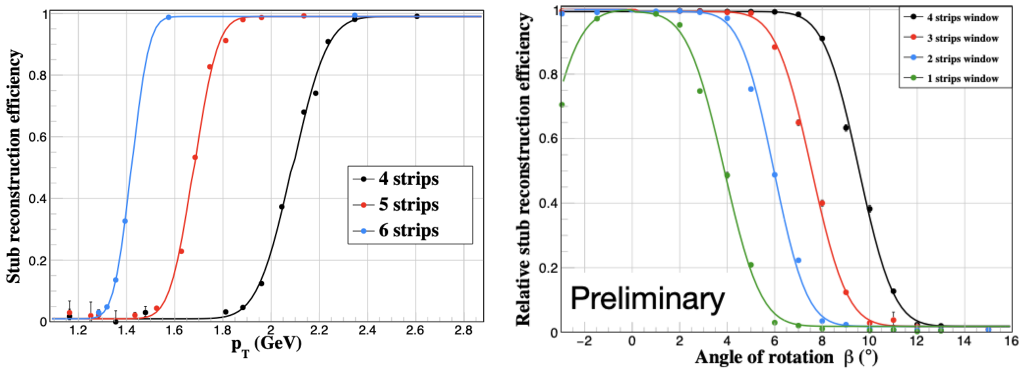

Figure 5: Left: Stub efficiency as a function of the emulated p_T for a 2S prototype [17]. Right: Stub efficiency as a function of the beam incidence angle for a PS prototype. Different lines in the plot refer to the width of the stub search windows.

Prototypes are also used in integration tests: One full TB2S ladder has been populated with 2S modules and tested; both 2S and PS modules have been mounted together on a TEDD Dee; a TBPS plank with one PS module was successfully cooled down with a $C0_2$ cooling system. In all cases valuable lessons for the final system integration could be obtained.

A complete set of quality control tests is implemented for the modules and their components [18, 19]. Module production sites are being 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 the operation temperature (around -35°C) over 24 hours to check for possible early mortality. During this time, modules will also go through calibrations and tests. Based on the results, the module will be graded and characteristics stored in the production database. These data will be then used to identify the best modules to be installed in the detector.

6. Conclusions

The CMS Phase-2 Outer Tracker will be able to identify hits from high-p_T tracks on detector with the help of the p_T modules concept and will provide information to the L1-trigger system. Several production centers in Europe, the US, and Asia will be involved in the multi-step assembly of the more than 13 000 modules required to assemble 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 2024.

Mechanical structures designed to guarantee hermetical coverage while minimizing the material budget will host the produced modules. 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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