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The Phase 2 Upgrade of the CMS Outer Tracker

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Abstract

The Large Hadron Collider (LHC), at CERN will undergo major upgrades to be able to deliver peak instantaneous luminosities of about $5 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ by 2027. This High Luminosity upgrade of the LHC (HL-LHC) is expected to deliver a total of about $3000 - 4000 \text{ fb}^{-1}$ during ten years of operation. At the nominal instantaneous luminosity of the HL-LHC, a single bunch crossing will produce $140 - 200$ proton-proton collisions. The current CMS strip tracker and the CMS Phase-1 pixel detector will not be able to survive the harsh operating conditions of the HL-LHC period. The CMS experiment will install a new silicon tracker for the HL-LHC. The Phase-2 Outer Tracker (OT) will feature increased radiation hardness, higher granularity and track separation and compatibility with higher data rates and a longer trigger latency. In addition, the OT will provide tracking information to the Level-1 trigger, allowing trigger rates to be kept at a sustainable level without sacrificing physics potential. To achieve this, the OT will be made up of modules with two closely spaced sensors read out by a single ASIC. The ASIC will correlate data from both sensors to form short track segments called stubs, to be used in tracking at Level-1. In this contribution, the design of the CMS Phase-2 OT, the technological choices and highlights of the research and development activities will be reported.

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The Phase-2 Upgrade of the CMS Outer Tracker

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Abstract

The Large Hadron Collider (LHC), at CERN will undergo major upgrades to be able to deliver peak instantaneous luminosities of about $5 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ by 2027. This High Luminosity upgrade of the LHC (HL-LHC) is expected to deliver a total of about $3000 - 4000 \text{ fb}^{-1}$ during ten years of operation. At the nominal instantaneous luminosity of the HL-LHC, a single bunch crossing will produce $140 - 200$ proton-proton collisions. The current CMS strip tracker and the CMS Phase-1 pixel detector will not be able to survive the harsh operating conditions of the HL-LHC period. The CMS experiment will install a new silicon tracker for the HL-LHC. The Phase-2 Outer Tracker (OT) will feature increased radiation hardness, higher granularity and track separation and compatibility with higher data rates and a longer trigger latency. In addition, the OT will provide tracking information to the Level-1 trigger, allowing trigger rates to be kept at a sustainable level without sacrificing physics potential. To achieve this, the OT will be made up of modules with two closely spaced sensors read out by a single ASIC. The ASIC will correlate data from both sensors to form short track segments called stubs, to be used in tracking at Level-1. In this contribution, the design of the CMS Phase-2 OT, the technological choices and highlights of the research and development activities will be reported.

1. Introduction

The LHC machine is getting upgraded to deliver an instantaneous luminosity of about $5 - 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ beyond 2027. This phase of the LHC

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operations will be termed as High Luminosity LHC (HL-LHC). As a result, during the HL-LHC period, the number of collisions per bunch crossing will rise to very high values, between 140 and 200. The HL-LHC is expected to deliver an integrated luminosity of about 3000 fb^{-1} [1, 2]. The current CMS tracker [3] will be damaged by the radiation received during the Run 1 - Run 3 operations of the LHC. The CMS Collaboration will install a new radiation hard silicon tracker with the capability to operate over the planned HL-LHC period. Extensive studies have been done to optimize the design of the Phase-2 tracker for high granularity, enabling tracking even in the high number of collisions per bunch crossing (140 – 200), reduced material budget and the ability to participate in the Level 1 (L1) trigger decision. The current L1 trigger system in the CMS experiment (which uses information from the calorimeters and the muon systems) will not be able to sustain the HL-LHC event rate and thus tracking information at L1 is important to allow CMS to collect data without losing physics potential.

2. Layout of the Phase-2 tracker

The layout of the proposed CMS tracker as shown in Fig. 1 will have two parts - a barrel section, made out of cylindrical layers, and two endcaps at either end of the barrel, made out of discs. The innermost region of the barrel will be made out of four layers of pixel detectors called the Inner Tracker (IT). The IT will provide three-dimensional hit coordinates allowing excellent vertex identification. The IT barrel detector will be followed by six layers of the Outer Tracker detector (OT). The barrel OT will be made up of modules having two silicon sensors separated by a few millimeters. These modules, also known as p_T modules, will be capable of discriminating high p_T tracks from low p_T ones. The concept of p_T discrimination will be discussed in the following section. Out of the six layers of the barrel OT, three layers immediately after the inner pixel layers will comprise modules made of one pixelated sensor and one micro-strip sensor (**PS** p_T module). The PS modules in the barrel layers will be progressively tilted as one moves towards the forward direction, as shown in Fig 1. The next three outer layers will be instrumented with modules with two micro-strip sensors (**2S** p_T module). The endcap discs feature a similar arrangement of inner pixels, **PS** and **2S** modules radially moving outwards from the beam-line, as shown in Fig. 1.

Figure 1: Sketch of one quarter of the tracker layout in $r - z$ view [4]. The radial region below 200 mm is referred to as Inner Tracker and will be instrumented with pixel modules. In the Outer Tracker, the radial region between 200 and 600 mm is equipped with PS modules (blue lines), while the region beyond 600 mm will be populated with 2S modules (red lines). The CMS coordinate system is defined in Ref. [3].

2.1. The concept of p_T discrimination

In the presence of the CMS magnetic field of 3.8 T the final state charged particles of the event will bend in a plane transverse to the direction of the beam. The radius of curvature of the trajectory of these particles will depend on the particle p_T . The concept of p_T discrimination is shown in Fig. 2. As a charged particle passes through the module, it generates signals (hits) in the bottom and top sensors within the module. A hit in the bottom sensor is then matched to the one in the top sensor and if they are within a predefined window, these two hits are combined to form a short track segment or **stub**. These stubs are used later in L1 tracking. The readout of the modules will be binary and the readout chips will be programmed to provide the p_T discrimination logic described above. The window for hit matching can be set within the readout chip according to the p_T threshold to be used.

3. OT modules

The OT will be made out of two types of p_T modules. The main specifications of the full size **PS** and **2S** modules for the OT are given in Table 1. The 2S module is read out by the CMS Binary Chip (CBC) [5, 6, 7, 8, 9]. Each CBC has 254 readout channels with alternate channels connected to the top and bottom sensors in a module. The 2S module, shown in Fig. 3 (left), consists of two sensors (n-type strips in p-type silicon substrate), support

Figure 2: Illustration of the p_T module concept [2]. Correlation of signals in closely spaced sensors enables rejection of low- p_T particles. The channels shown in green represent the selection window to define an accepted stub; a low- p_T rejected track is shown in red.

structures made from Al-CF (carbon fibre reinforced aluminium), two front-end hybrids, each with eight CBCs, and a service hybrid [10] for powering and output data serialization followed by opto-electrical conversion. The PS modules (Fig. 3 (right)) will have two different types of the readout chips since the bottom sensor is pixelated. The bottom sensor will be read out by the Macro Pixel ASIC (MPA) [11], whereas the strip sensor will be read out by the Short Strip ASIC (SSA) [12]. The correlation of strip and macro-pixel hits to build stubs will be programmed in the MPA chip. The MPA ASIC is bump bonded to the macro-pixel sensor. Both PS and 2S modules will also have one concentrator integrated circuit (CIC) [13] per front-end hybrid that aggregates data from the CBCs or MPAs and sends them to the low-power Gigabit Transceiver (LpGBT) [14] chip on the service hybrid. The Versatile Transceiver+ (VTRx+) [15] converts the data from an electrical to optical signal, and sends them to the back-end electronics.

Table 1: Main parameters of the 2S and PS modules of the proposed CMS Phase-2 tracker [2].

2S module			PS module		
$\sim 2 \times 90 \text{ cm}^2$ active area			$\sim 2 \times 45 \text{ cm}^2$ active area		
No. of strips/sensor plane	Strip length	Pitch	No. of strips/macro-pixels	Strip/macro-pixel length	Pitch
2×1016	$\sim 5 \text{ cm}$	$90 \text{ } \mu\text{m}$	$2 \times 960/32 \times 960$	$\sim 2.4 \text{ cm}/\sim 1.5 \text{ mm}$	$100 \text{ } \mu\text{m}$

An extensive characterization and irradiation program was undertaken by the CMS Collaboration to identify the sensor choice for the OT. Two

Figure 3: Left: 2S module of the OT. Right: PS module of the OT. The top figures show the assembled modules, whereas the bottom figures show the connection of the front end hybrid to the sensors [2].

different sensor types were studied - Deep Diffused Float Zone (FZ) n-in-p type silicon with an active thickness of $290\text{ }\mu\text{m}$, referred to as FZ290 later, and thinned FZ sensors of $240\text{ }\mu\text{m}$ active thickness, referred to as thFZ240. The modules were irradiated to the maximum expected fluences for an integrated luminosity of 3000 fb^{-1} and their properties were studied. The value of $3 \times 10^{14}(1 \times 10^{15})\text{ n}_{\text{eq}}/\text{cm}^2$ corresponds to max expected fluence of the 2S(PS) modules after 3000 fb^{-1} of irradiation, as well as for 95% of 2S(PS) modules after 4000 fb^{-1} of irradiation. The highest fluence taken into consideration are $6 \times 10^{14}(1.5 \times 10^{15})\text{ n}_{\text{eq}}/\text{cm}^2$, which includes safety factor of +50 (+12.5)% for the 2S (PS) modules over the expected fluence after 4000 fb^{-1} . Since the modules of the OT have a binary readout, the important quantity to study is the charge of the strip with the highest charge collected (seed) and not the charge of the cluster. The charge of the seed has to cross the threshold in order to register the hit. The seed signal of the strip sensors after irradiation is shown in Fig. 4. It can be seen that the FZ290 performs better and provides sufficient signal at the standard operating voltage of 600V to operate up to the maximum fluence expected after 3000 fb^{-1} whereas thFZ240 sensors can barely reach the required thresholds even after very long annealing. Thus, the FZ290 sensors were chosen for the OT modules.

A schematic representation of the back-end electronics for the OT modules along with the data flow to the L1 trigger system is shown in Fig. 5. The stub information from the modules is sent to the Data, Trigger and Control

Figure 4: Seed signal as a function of annealing time for FZ290 (blue) and thFZ240 (green) strip sensors after irradiation to the maximum expected fluences after 3000fb^{-1} for the 2S (top) and PS (bottom) modules. Solid (open) points refer to signal collected with a bias voltage of 600 (800) V. The horizontal lines represent the required signal for the 2S and the PS strip (PS-s) sensors.

board (DTC). One DTC board receives stubs from up to 72 modules. Stubs in global coordinates are sent to the Track Finder Processor (TFP). The TFP performs pattern recognition and track finding on commercially available FPGAs. Three different approaches for pattern recognition were studied and put to test with a hardware demonstrator [2]. All approaches were successful in delivering tracks to the L1 trigger system within the allowed latency of $4\ \mu\text{s}$. A hybrid approach of combining two of those algorithms is currently being explored by the CMS Collaboration [16].

Figure 5: A schematic representation of the data flow from the OT modules to the L1 trigger system [17].

4. Performance of prototype modules in beam tests

Prototype modules of the OT have been studied at various test beam facilities at CERN, Fermilab and DESY [2, 18, 4]. Both full-size 2S prototype modules and 2S mini-modules read out by CBC version-2, (CBC2) chips were tested. PS micro-modules with two stacked small macro-pixel (PS-p) sensors read out by 6 MPA-light chips were also studied. The modules were placed in a reference telescope system, which was used to reconstruct the tracks of incoming particles. To emulate the effect of track bending in a magnetic field, the modules were rotated with respect to the beam direction. This allowed studies of cluster properties as a function of the rotation angle and verifying the p_T discrimination logic. Figure 6 (left) [4] shows the stub efficiency as a function of the incident angle for a non-irradiated 2S mini-module and a 2S mini-module irradiated to a fluence of $6 \times 10^{14}\ \text{n}_{\text{eq}}/\text{cm}^2$. As expected, for larger angles of incidence, which corresponds to smaller effective p_T , the stub efficiency drops. A radius of 60 cm was used for the calculation of emulated

p_T from the beam incident angle (α) using the formula p_T [GeV] $\approx \frac{0.57 \cdot R[\text{m}]}{\sin(\alpha)}$, assuming a magnetic field of 3.8 T. The stub correlation window is set to 5 strips. Figure 6(right) [2] shows the fraction of reconstructed stubs in a micro-module as a function of emulated p_T , for various values of Δx , where Δx stands for the distance in units of macro-pixels between the clusters in the top and bottom sensor. A radius of 51.7 cm was used for the conversion of beam incident angle to p_T . The results demonstrate the principle of p_T discrimination logic of the OT modules, as described in Section 2.1.

Figure 6: Left: stub efficiency for the irradiated (blue) and non-irradiated (red) 2S mini-modules as a function of the beam incident angle (upper x axis), and the corresponding emulated p_T (lower x axis) [4]. Right: fraction of reconstructed stubs in a PS micro-module as a function of emulated p_T for various correlation window sizes in units of macro-pixels [2].

5. Performance from simulation

The performance of the track reconstruction has been studied using different types of simulated events and under two pileup scenarios - 140 and 200 [2]. The tracking efficiency as a function of pseudorapidity (η) is shown in Fig. 7 for single muon events. The efficiency is stable and close to 100% for the entire η range for both pileup scenarios. Despite the increase in total surface area of silicon in the Phase-2 OT compared to the current tracker, the material budget is lower compared to the current tracker. This has been achieved by using an efficient powering scheme, serial powering for the IT and DC-DC conversion for the OT, by using two-phase evaporative CO₂ cooling, which allows us to use cooling pipes with a diameter of about 2 mm, and due to the tilted geometry in the PS layers in the barrel region.

Figure 7: Track reconstruction efficiency as a function of pseudorapidity (η) for single muon events [2].

The lower material budget helps to achieve better p_T and transverse impact parameter resolutions. The relative resolution of the transverse momentum (left) and the resolution of the transverse impact parameter (right) as a function of the pseudorapidity can be seen in Fig. 8. The plots also show that the Phase-2 tracker will provide extended pseudorapidity (η) coverage compared to the current tracker. These results demonstrate that the tracking performance will be excellent even at the high pileup expected at the HL-LHC. More results on the expected performance of track reconstruction can be found in Refs. [1, 2].

6. Conclusion and outlook

The CMS Collaboration will install a new silicon tracker for the HL-LHC operations, where the IT will be made out of silicon pixel modules and the OT will be made out of modules with two stacked silicon sensors. The main feature of the OT modules will be to correlate hits on the two sensors depending on the p_T of the incident particle. This will allow tracking at the L1 trigger system enabling CMS to collect data in the HL-LHC period without limiting physics potential. After detailed characterization and irradiation studies, the CMS collaboration has finalized the choice of silicon sensors for the OT. Prototype modules of the OT have been studied in beam tests

Figure 8: Relative resolution of the transverse momentum (left) and resolution of the transverse impact parameter (right) as a function of the pseudorapidity (η) for the Phase-1 tracker (black dots) and the Phase-2 tracker (red triangles) [2].

and the modules have demonstrated the power of rejecting tracks below a certain p_T . The CMS Collaboration is now preparing for the production of the components of the Phase-2 tracker.

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