The CMS Outer Tracker for HL-LHC

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Abstract

The LHC is planning an upgrade program, which will bring the luminosity to about $5 - 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2026, with a goal of an integrated luminosity of 3000 fb$^{-1}$ by the end of 2037. This High Luminosity LHC scenario, HL-LHC, will require a preparation program of the LHC detectors known as Phase-2 Upgrade. The current CMS Tracker is already running beyond design specifications and will not be able to cope with the HL-LHC radiation conditions. CMS will need a completely new Tracker in order to fully exploit the highly demanding operating conditions and the delivered luminosity. The new Outer Tracker system is designed to provide robust tracking as well as Level-1 trigger capabilities using closely spaced modules composed of silicon macro-pixel and/or strip sensors. Research and development activities are ongoing to explore options and develop module components and designs for the HL-LHC environment. The design choices for the CMS Outer Tracker Upgrade are discussed along with some highlights of the R&D activities.

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Keywords: silicon sensors, tracking, radiation hardness

1. Introduction to HL-LHC and the Outer Tracker Upgrade of CMS

The Large Hadron Collider (LHC) at CERN will undergo an extensive upgrade program during the long shutdown 3 (2024-2026) to reach unprecedented performance. The instantaneous luminosity will reach $5\times10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ and the integrated luminosity will reach $3000\text{ fb}^{-1}$ (up to $4000\text{ fb}^{-1}$, if the ultimate instantaneous luminosity can be achieved). As consequences of the increased performance the detector has to cope with increased radiation levels and more collisions within one bunch crossing (pile-up). The current trigger system of CMS would not be capable of efficiently selecting the interesting events. It was shown that the track information from the tracking system can significantly improve the performance of the Level-1 (L1) trigger, which is the first instance of the trigger system. That necessitates to provide the relevant tracks for each bunch crossing. This is the main requirement that drives the layout and concepts of the new Outer Tracker for the HL-LHC phase. Further requirements and corresponding implementations are listed in Tab. 1.

2. Design of the new Outer Tracker for CMS

Figure 1 shows the layout of the planned CMS Tracker. The Outer Tracker (radius $r$ larger than 200 mm) contains only two types of modules, which are made of a stack of silicon sensors, tracking, radiation hardness
two silicon sensors with a gap of 1.6 to 4.0 mm. These modules are specially designed to provide hits for each bunch crossing. The 13296 modules are arranged in barrel layers in the center and as double discs in the endcap regions. The inner barrel has a novel tilted geometry for better tracking and reduced number of modules (i.e. lower material budget and costs), which is illustrated in Fig. 2. The temperature of the modules is controlled via two-phase CO$_2$ cooling (around $-33^\circ$C) being distributed with thin pipes also reducing the material budget. The electronic components on the modules are powered via DC-DC converters, which convert 11 V input voltage to the desired lower voltages. This reduces the required cable mass considerably. All these implementations lead to a new tracker with reduced material in the tracking region and better performance at high pile-up than the current tracker at CMS.

3. $p_t$-module concept, Track Finder and L1-trigger

The design of the modules is driven by the need of hit information for each bunch crossing. It is not possible to transfer all hit information to the back-end readout system and therefore, the module needs to select relevant hits thus reducing the amount of data being transmitted for each bunch crossing (while keeping all hit data in the readout chip buffers for a final trigger decision up to 12.5$\mu$s later). This selection is performed by applying a cut on the transverse momentum of charged particles, which can be exploited in the high magnetic field of CMS. A programmable search window allows to select straight, i.e. high momentum, particles as illustrated in Fig. 3. A cut corresponding to 2 GeV$/c$ already removes 99% of the particle tracks. The accepted short track segments including the position and bend information, referred to as stubs, are transferred to the back-end via high-speed optical links and further to the Data, Trigger and Control (DTC) system and Track Finder. In this path the data is processed and fitted track parameters are provided to the L1-trigger system within 4$\mu$s. This massive computation task will be highly parallelized (time-multiplexing) and performed on many Track Finding Processors based on FPGAs as a reference system.

4. Module types and assembly

The inner modules of the Outer Tracker consist of strip sensors (2x960 strips with pitch of 100$\mu$m and length of 2.5 cm) and pixel sensors (32x960 macro-pixel with pitch of 100$\mu$m and length of 1.5 mm) and are called PS modules. This module type is illustrated in Fig. 4. The strip sensors of the PS module are connected to the strip sensor ASIC (SSA), which sends hit information to the macro-pixel ASIC (MPA), where the required correlation of hits in the upper strip sensor and the lower macro-pixel sensor is performed. These modules provide higher granularity due to the short macro-pixels, which is required for
Figure 5: Drawing of the 2S module type. Shown is the exploded view of parts as they need to be assembled at the module assembly sites.

Figure 6: Illustration of the electrical connectivity of the front-end hybrid to the sensors on the 2S module.

A good vertex resolution along the beam direction for L1-tracks. The expected maximum fluence for PS modules is $9.6 \times 10^{14}\text{n}_\text{eq}/\text{cm}^2$ after 3000 fb$^{-1}$.

The 2S modules consist of 2 strip sensors (2x1024 strips with pitch of 90 $\mu$m and length of 5 cm) (Fig. 5). The readout chips (CMS Binary Chip, CBC) are connected to the upper and lower sensors via metal routing lines on the flex hybrid.

Both module types contain all necessary readout (readout chips as well as aggregation and formatting stage) and service (power and communication) components and are operated as standalone readout entities. The expected maximum fluence for 2S modules is $3 \times 10^{14}\text{n}_\text{eq}/\text{cm}^2$ after 3000 fb$^{-1}$.

A crucial aspect for both module types is the connection of the individual readout chips to both sensor layers. This is realized by flex Kapton hybrids bent around a stiffener providing bond pads on both sides and traces to connect to the bump bonded readout chips. This is illustrated in Fig. 6 for the 2S module, but the concept applies to both module types.

The assembly of such modules demands very high precision on the parallelism of the upper and lower sensor strips or pixel columns. An angle between the sensors would cause the programmed search window to move depending on the hit location along the strip. This in turn affects the $p_T$-resolution and deteriorates the efficiency of the $p_T$-discrimination for L1-tracks. The requirement on the angle between the upper and lower strips is set to 400 $\mu$rad for 2S modules (800 $\mu$rad for PS), and motivated by the fact that the strips should not deviate more than $\pm 20\mu$m (less than half the pitch) along their length. Parallel offsets can be accounted for by configuring the chips accordingly and are not affecting the stub finding. The necessary accuracy is achieved by exploiting the good dicing precision (standard quality without requesting high accuracy) of the sensor manufacturers and assembly jigs with precision alignment pins. Methods to monitor the rotation between the upper and lower strips have been developed.

5. Examples from prototyping

This section shows examples of the ongoing developments and prototypes for the above introduced upgrade.

5.1. Sensors

Sensors with n-type electrodes in p-type silicon bulk were chosen as the baseline technology. It was shown that proper strip isolation can be achieved by both p-stop and p-spray technologies. Irradiation studies with samples of different p-stop concentrations recommend a moderate implantation dose to reduce high field induced noise or breakdown effects.

Full-size 2S sensors have been produced with the baseline layout and characterized to meet the specifications. Strip sensors with active thicknesses of 200 $\mu$m, 240 $\mu$m and 300 $\mu$m were tested for their radiation hardness. The aims were a high signal over threshold and a stable annealing behavior. The latter was found for strip sensors with a thickness of 240 $\mu$m and below as shown in Fig. 7. The most probable value (MPV) of the signal distribution should be three times above the threshold to be highly efficient and the threshold should be set to about four times the noise to reduce the faction of falsely identified hits to less than $10^{-4}$. This results in a factor of twelve higher MPV of the seed signal (seed signal is more relevant than cluster signal due to the applied threshold cut)
compared to the the noise figure of the readout chip with attached sensor. Sensors for 2S modules are required to provide a signal of 12 000 electrons due to a noise of about 1000 electrons, while strip sensors of the PS module (SSA chip with about 700 electrons noise connected to a 2.5 cm long strip) should exceed 8400 electrons. For macro-pixel sensors 4000 electrons are sufficient. Therefore, the current baseline is 240µm for strip sensors and 200µm for macro-pixel.

5.2. Modules

A first prototype module for the demonstration of stub finding was assembled from two small sensor prototypes and a rigid front-end hybrid containing two CBC chips of version 2. The sensors have 256 5 cm long strips at 90µm pitch and are spaced by about 3mm. Such modules (Fig. 8 left) are rotated in a particle beam (at CERN SPS and DESY) to emulate the bending of the particles in the detector’s magnetic field. Fig. 9 demonstrated that the stub finding works efficiently before and after irritating the modules to about double the expected fluence. Finally, full-size 2S modules (Fig. 8 center) were assembled and characterized in particle beams (at CERN and FNAL) confirming good uniformity of the hit detection efficiency over the module width. Such a large module was also used to study the influence of the DC-DC powering with a prototype service hybrid containing shielded air coils as inductors. Fig. 10 shows that the noise of the closest CBC increased slightly compared to direct powering but stayed below the specified 1000 electrons.

Also a small version of the macro-pixel sub-assembly (six small macro pixel ASICs bump bonded to a miniature macro-pixel sensor; Fig. 8 right) was designed and several assemblies produced. They were successfully operated at test beams and show, as indicated in Fig. 11, very high efficiency in a wide window of the clock phase.

5.3. Mechanics

The new mechanical challenge is the tilted geometry for the inner layers housing PS modules and to provide the large area cooling joints for this module type. The inner layers are grouped in ring structures, which provide cold surfaces on which the modules can be glued (Fig. 12). In the endcaps the cooling joints are embedded in the carbon-fiber sheets. A small prototype section was produced to learn about the manufacturing process and to study the transition region between the inner region populated with PS modules and the outer region populated with 2S modules. An image showing the measured temperature distribution with this prototype is presented in Fig. 13.

5.4. Track Finder

The feasibility of track finding within the given time window of 4µs, transverse momentum resolution of about 2%, longitudinal vertex position resolution of about 1 mm
and a significant rate reduction of 1/100 was demonstrated in hardware by three approaches [5]. All of them need to go through four stages: data organization, pattern recognition, track fitting and duplicate removal. The data is grouped in regions and the hardware multiplied for time-multiplexing. One approach also uses associative memory chips for the pattern recognition [13], the other two are pure FPGA based [14, 15]. The latter have been chosen to be further developed on common hardware to optimize the FPGA-only reference system [5].

6. Conclusion and Outlook

All the new concepts of the upgraded CMS Tracker have been validated and the corresponding Technical Design Report was approved by December 2017 [5]. The community will increase the quantity of prototypes to finalize the assembly processes and to allow more intensive system and integration tests. The quality assurance for all parts is being reviewed and quality control mechanisms will be detailed.

The prototyping phase will continue with focus on large-scale production until pre-series productions are launched around 2020/21. The installation and commissioning of the final detector is foreseen for 2025.